University of Oxford - BETA-CAE Systems contribution to HiLiftPW-3

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Motivation

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- 1st High Lift Workshop participation
- Currently use OpenFOAM as turbulence modelling development – easy to collaborate globally
- Extensively used within major automotive companies e.g Audi, Mercedes F1
- Is the code accurate/robust enough for compressible complex aerospace cases?
- No particular bias towards the code – honest evaluation

Summary of cases completed: STAR-CCM+, ANSA-Unstructured, SA

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Case	Alpha=8, Fully turb, grid study	Alpha=16, Fully turb, grid study	Other
1a (full gap)	yes	yes	
1b (full gap w adaption)	no	no	
1c (partial seal)	no	no	
1d (partial seal w adaption)	no	no	

Case	Polar, Fully turb	Polar, specified transition	Polar, w transition prediction	Other
2a (no nacelle)	yes	no	no	
2b (no nacelle w adaption)	no	no	no	
2c (with nacelle)	no	no	no	
2d (with nacelle w adaption)	no	no	no	

Case	2D Verification study	Other
3	yes	

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Case	2D Verification study	Other
3	yes	

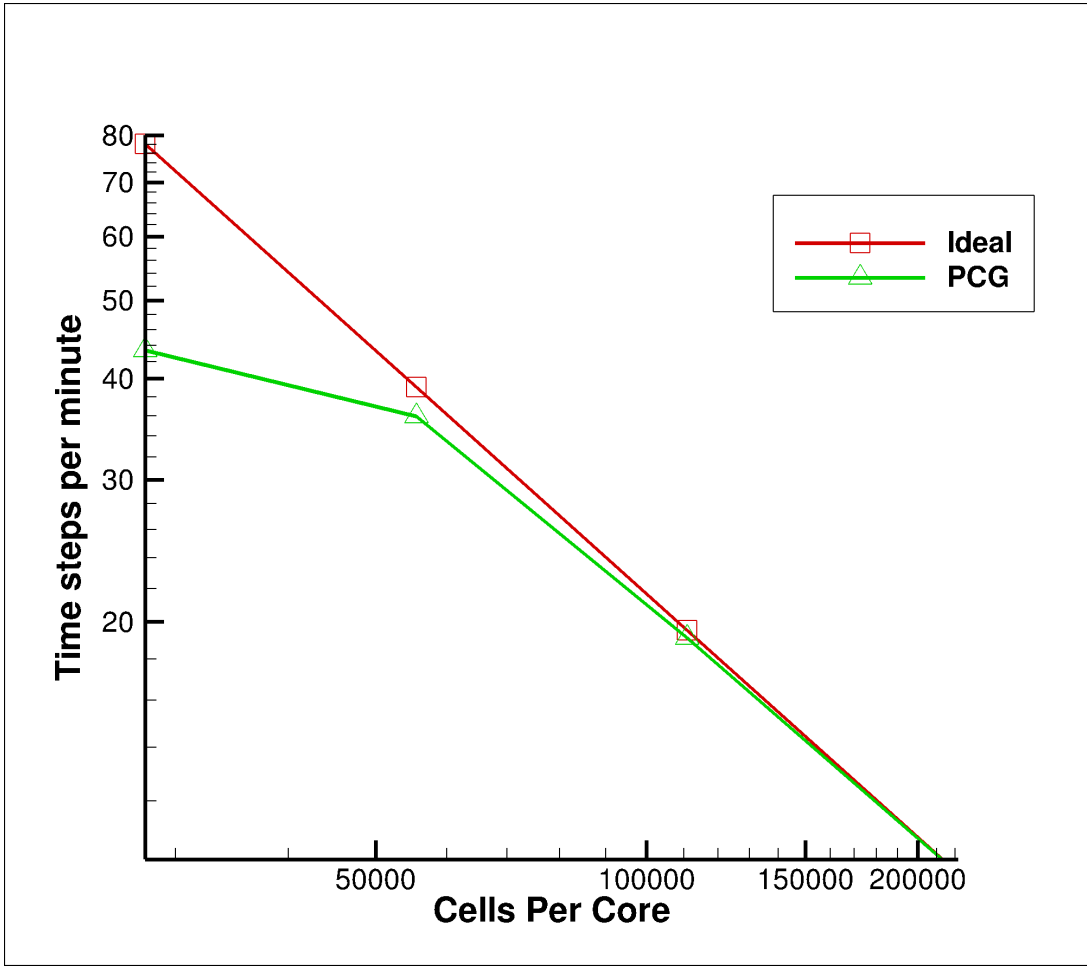
Summary of codes used

- **STAR-CCM+ v11.06**
  - Compressible coupled implicit density based
  - AMG Multi-grid
  - Roe Scheme
  - 2nd order upwind Momentum + Turbulence
  - CFL 5-10
  - SA Model (original production term to match org. SA)

- **OpenFOAM 4.1**
  - Compressible implicit segregated pressure-based solverwith local-time stepping to reach steady-state
  - Preconditioned Conjugate Gradient (because of AMG not scaling well enough)
  - 2nd order upwind Momentum + Turbulence
  - SA-no-ft2

Summary of computational resources

- STAR-CCM+ simulations run on ~480 cores - Oxford ARC system
- OpenFOAM - UK National Supercomputer; ARCHER
- Production runs typically on 1920-3840 cores, but ran up to 7,680 cores.



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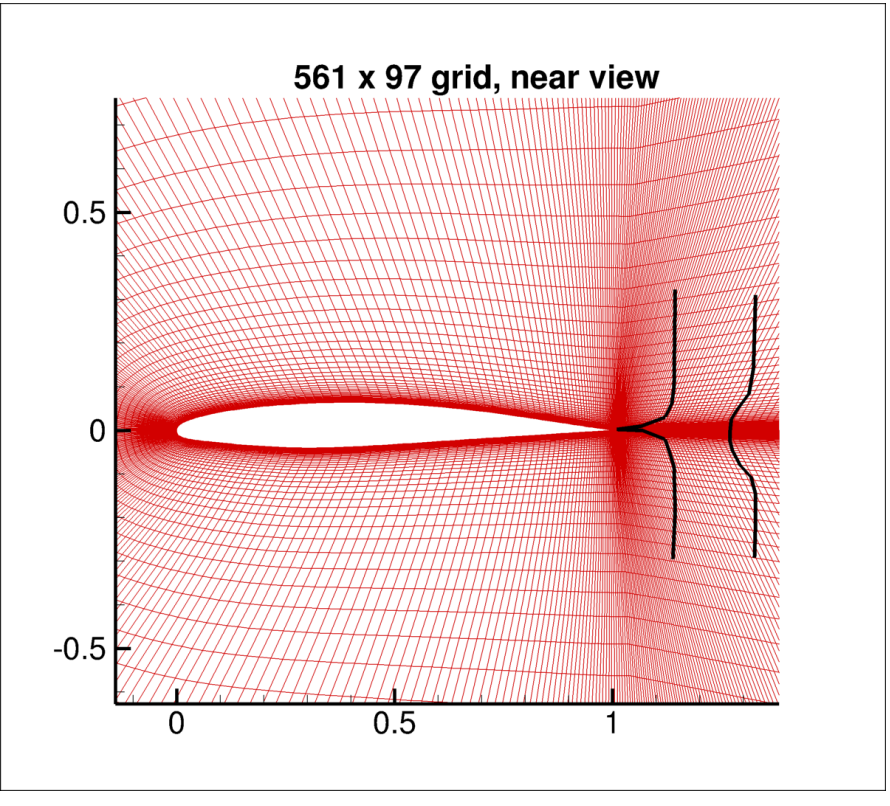
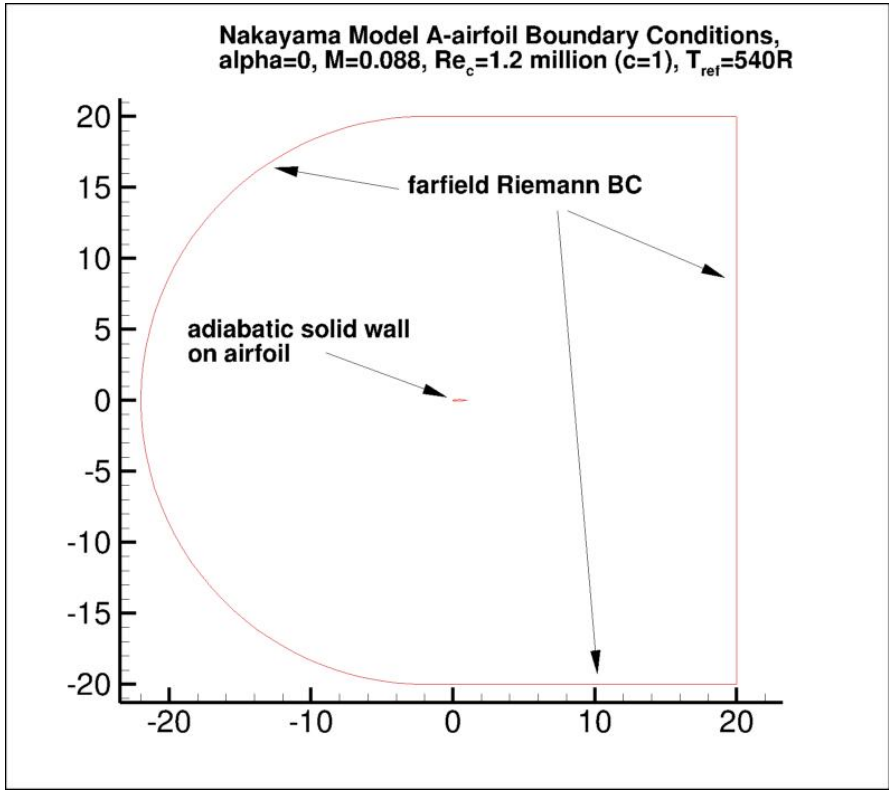
Verification

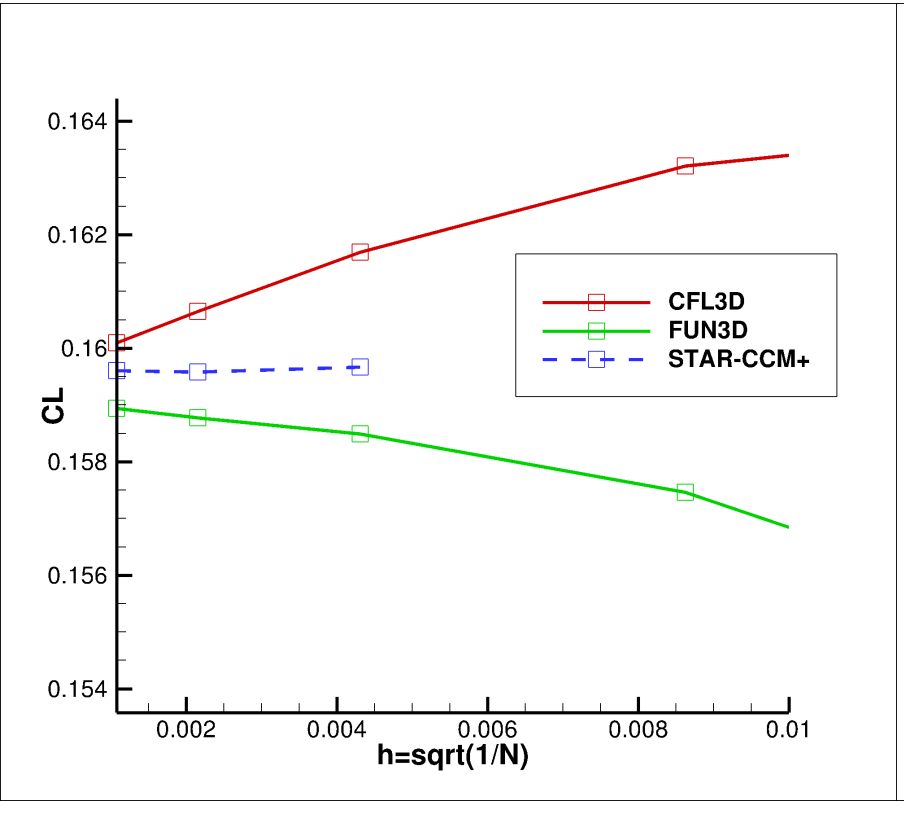
- Simple 2-D case of near-wake behind DSMA661(MODEL A) airfoil from NASA TMR website

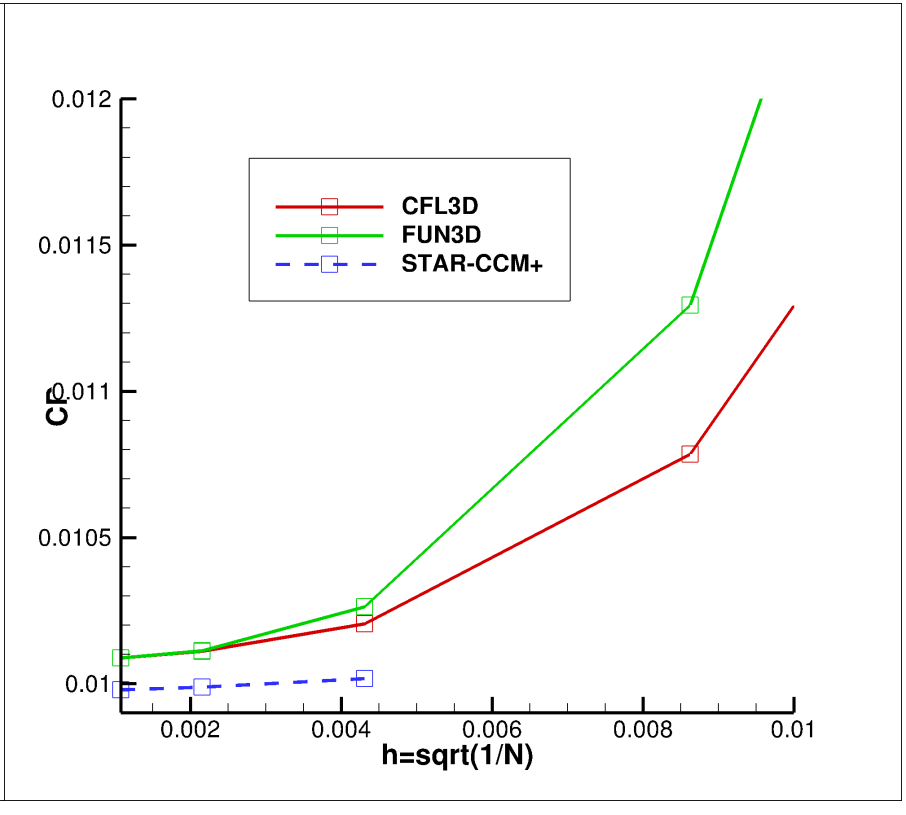




Verification study results – STAR-CCM+

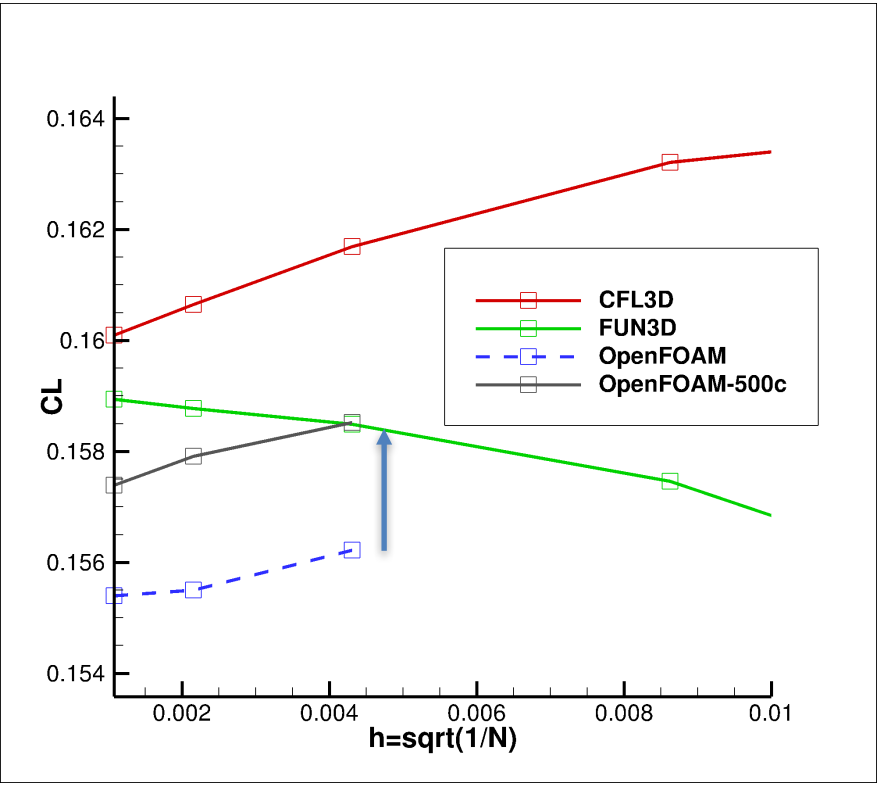
- Small constant offset for Drag, cannot check the exact formulation of SA model (no access to source code)
- 2nd order for turbulence may effect results

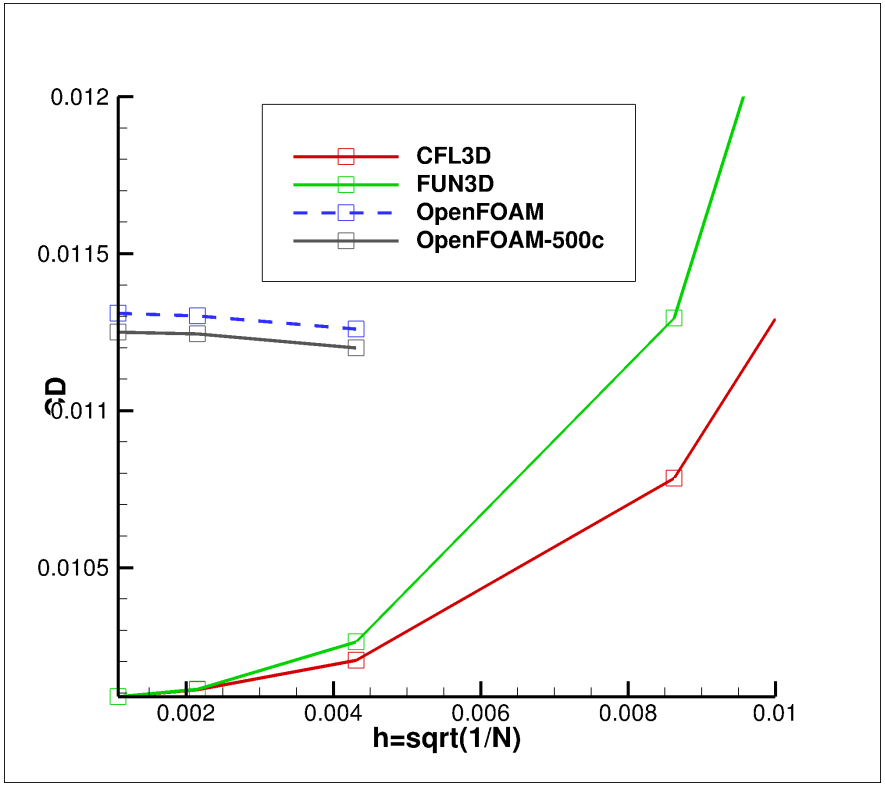




Verification study results – OpenFOAM

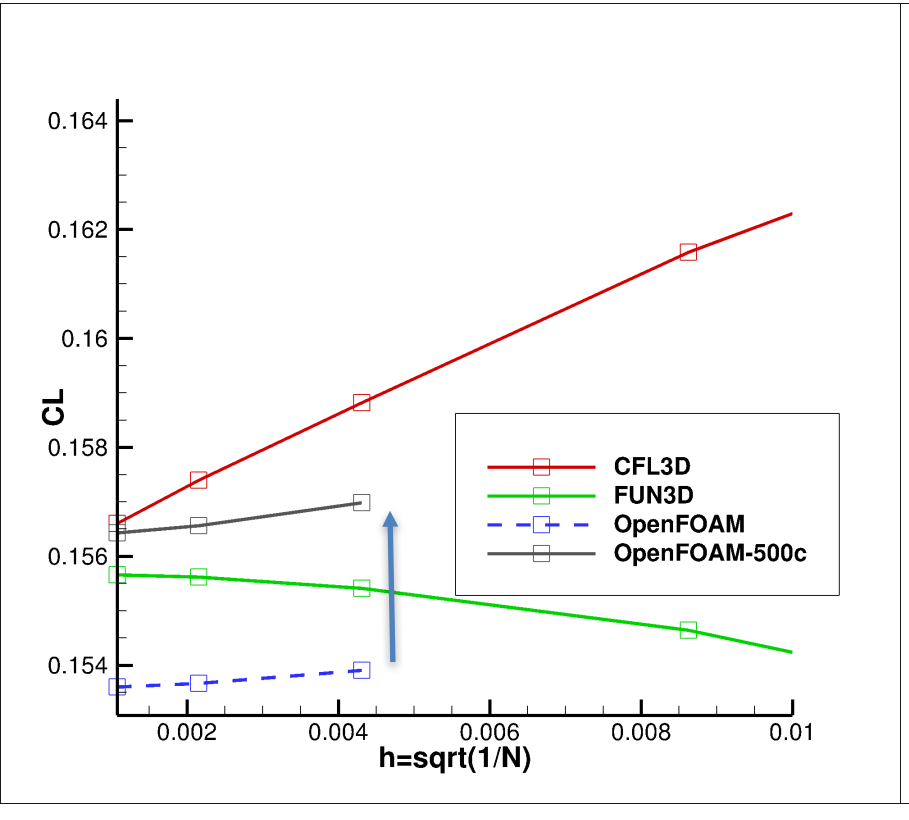
- OpenFOAM with standard grids suffers from too high drag and too low lift.
- Lack of farfield boundary condition and 20c domain
- Moving to 500c boundary brings Cl closer, but Cd is largely unaffected
- Suspect that it is wall-distance calculation

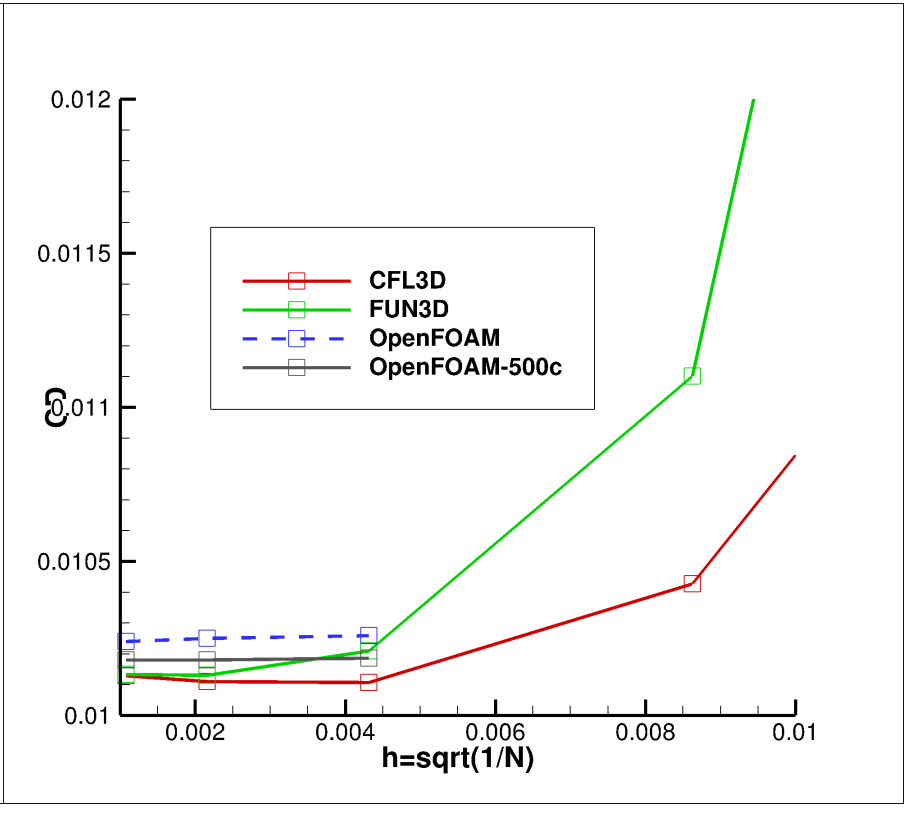




Verification study results – OpenFOAM -SST

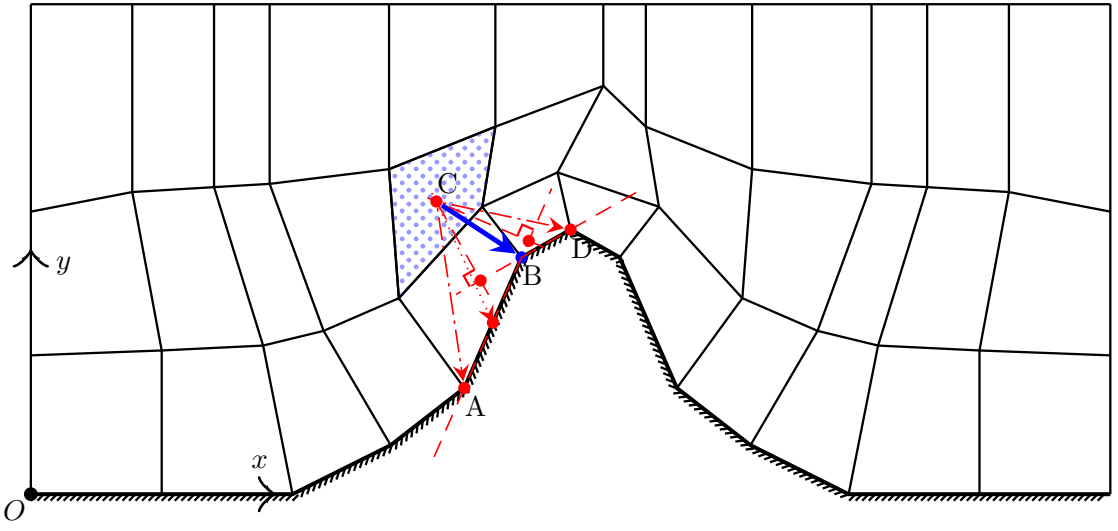
- Drag is close to CFL3D/FUN3D regardless of farfield
- 500c farfield brings lift very close to FUN3D/CFL3D
- Wall distance should have a much smaller effect – only in blending function of SST



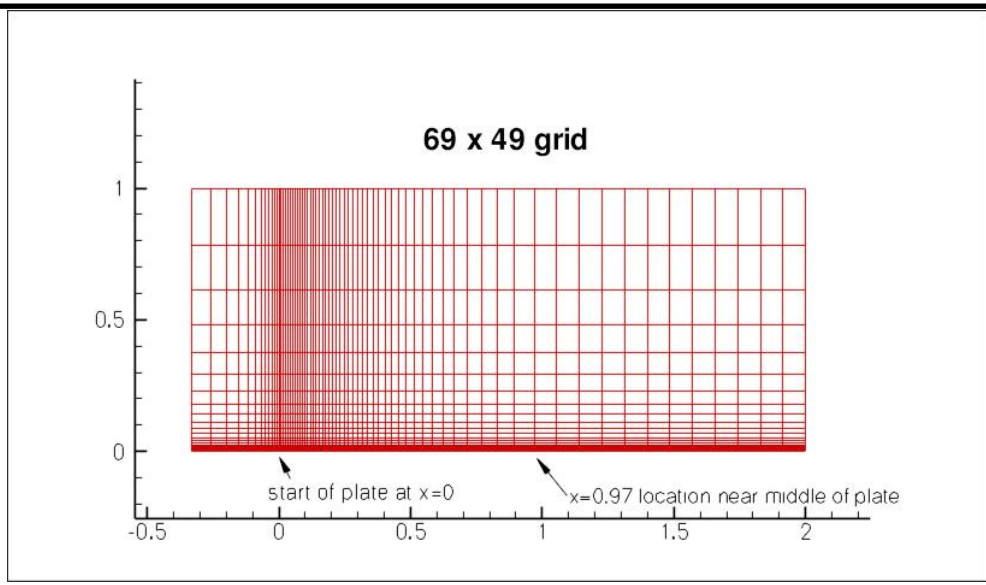


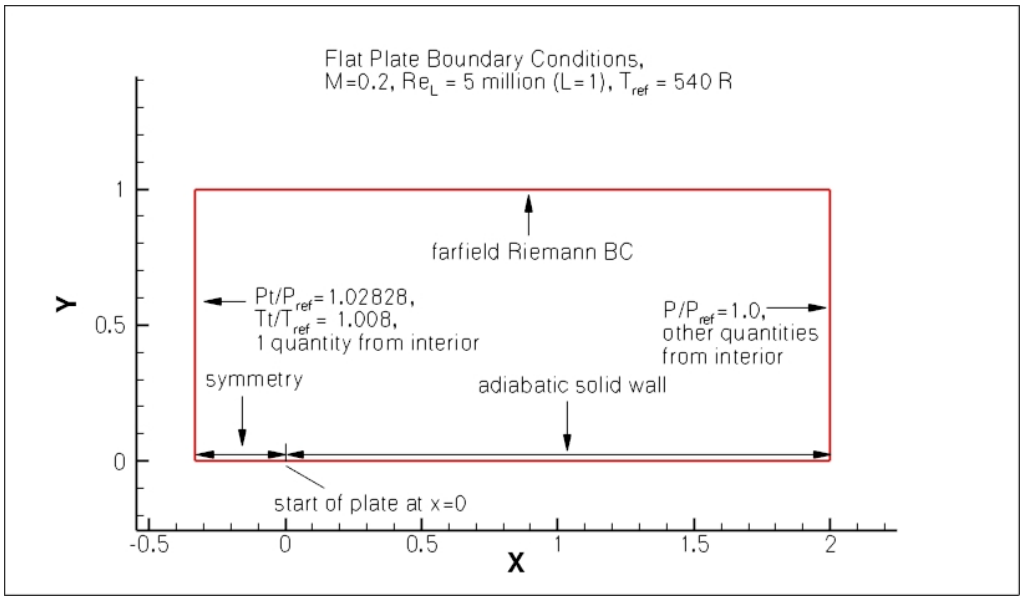
Wall-distance

- Recent work/investigation (found during the final HLPW simulations) –Thanks to Daniel Wei (Boeing) for discussions
- OpenFOAM computes nearest face center rather than closest point on wall
- Incorrect prediction of wall distance can lead to incorrect turbulent viscosity because wall-distance is key term in transport equation



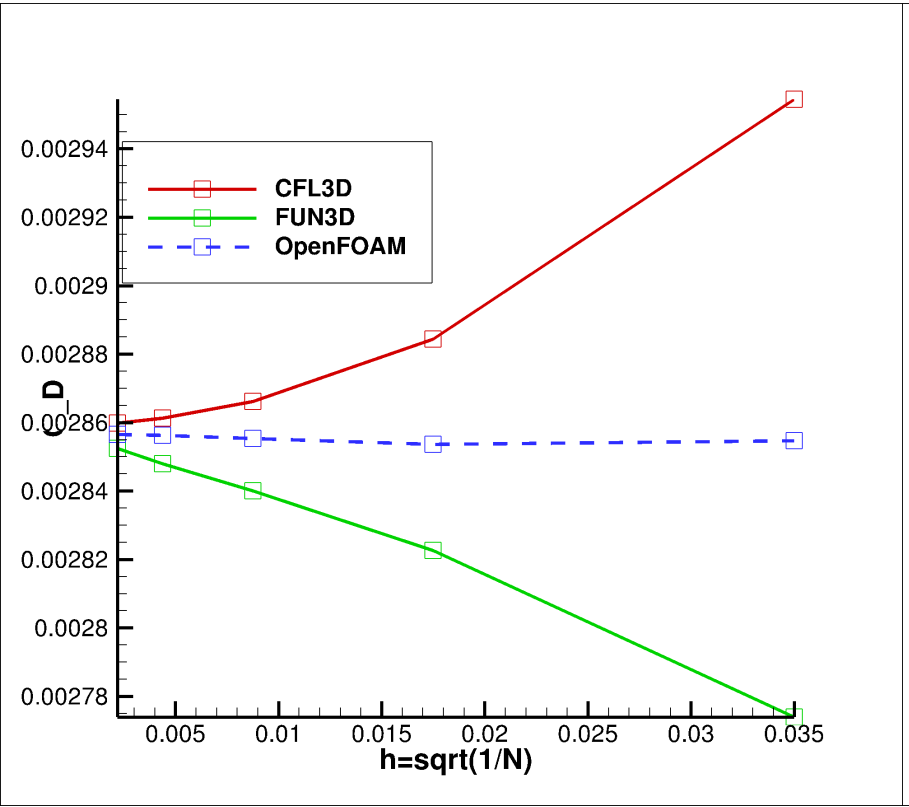
- ZPG Flat-Plate to test wall-distance
- Grid is orthogonal thus current OpenFOAM wall-distance is correct

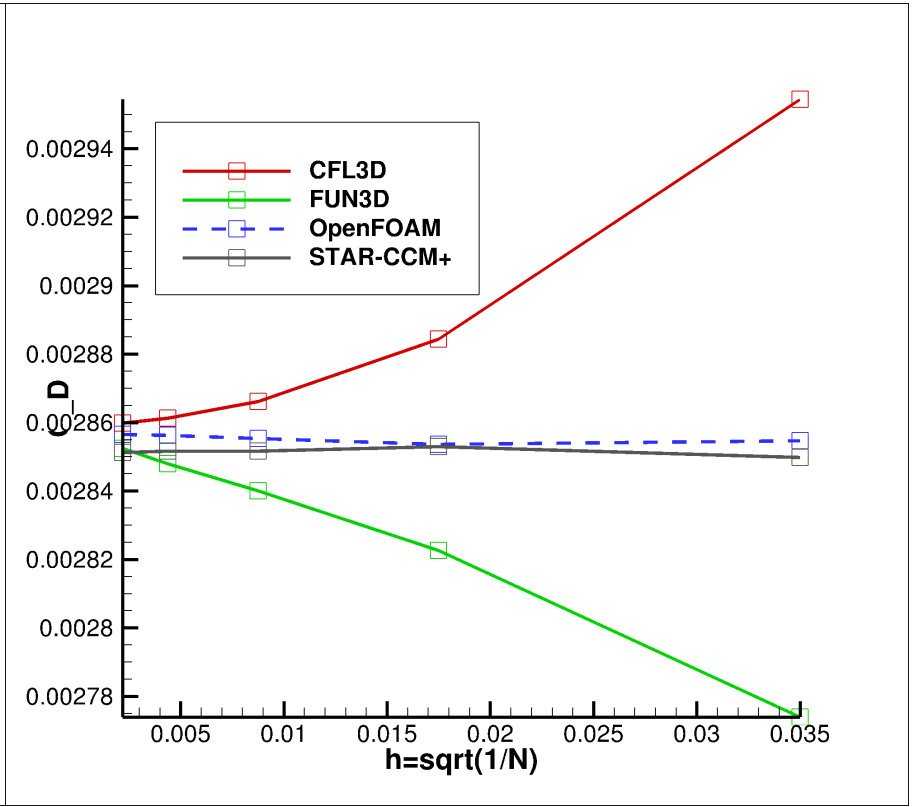




Flat-plate– OpenFOAM/STAR-CCM+

- OpenFOAM wall-distance should be correct for a flat-plate simulation with orthogonal, zero skewness cells
- Drag is in excellent agreement with CFL3D, FUN3D by finest grid
- Adds to hypothesis that major error on previous cases is from wall-distance on skewed cells/around edges etc





Verification conclusions

- Given verifications results, STAR-CCM+ has < 1 % error compared to FUN3D/CFL3D
- OpenFOAM has < 1% for the Lift but Drag is consistently higher – expect to see higher Drag for CRM/JSM cases
- Currently working to finally implement correct wall-distance into OpenFOAM – results should then agree well with other codes

Brief overview of grid systems

Grid System	Case(s)	If committee grid, report any problems/issues If user grid, reason for generating grid system
User (D-HLCRM_UnstrMixed_ANSA)	1a, 1b	
Committee (Hybrid Unstructured/E-JSM_UnstrMixed_ANSA)	2a, 2c	Generated grid system to have the same methodology for all cases

- Considerable time spent by BETA-CAE Systems to generate grids for all cases.
- Close collaboration between Oxford and BETA-CAE Systems meant grids went through several iterations before the final version.

- See dedicated presentation at 11.30am at Geometry and Meshing workshop on the grids

Summary of created meshes for the CRM model

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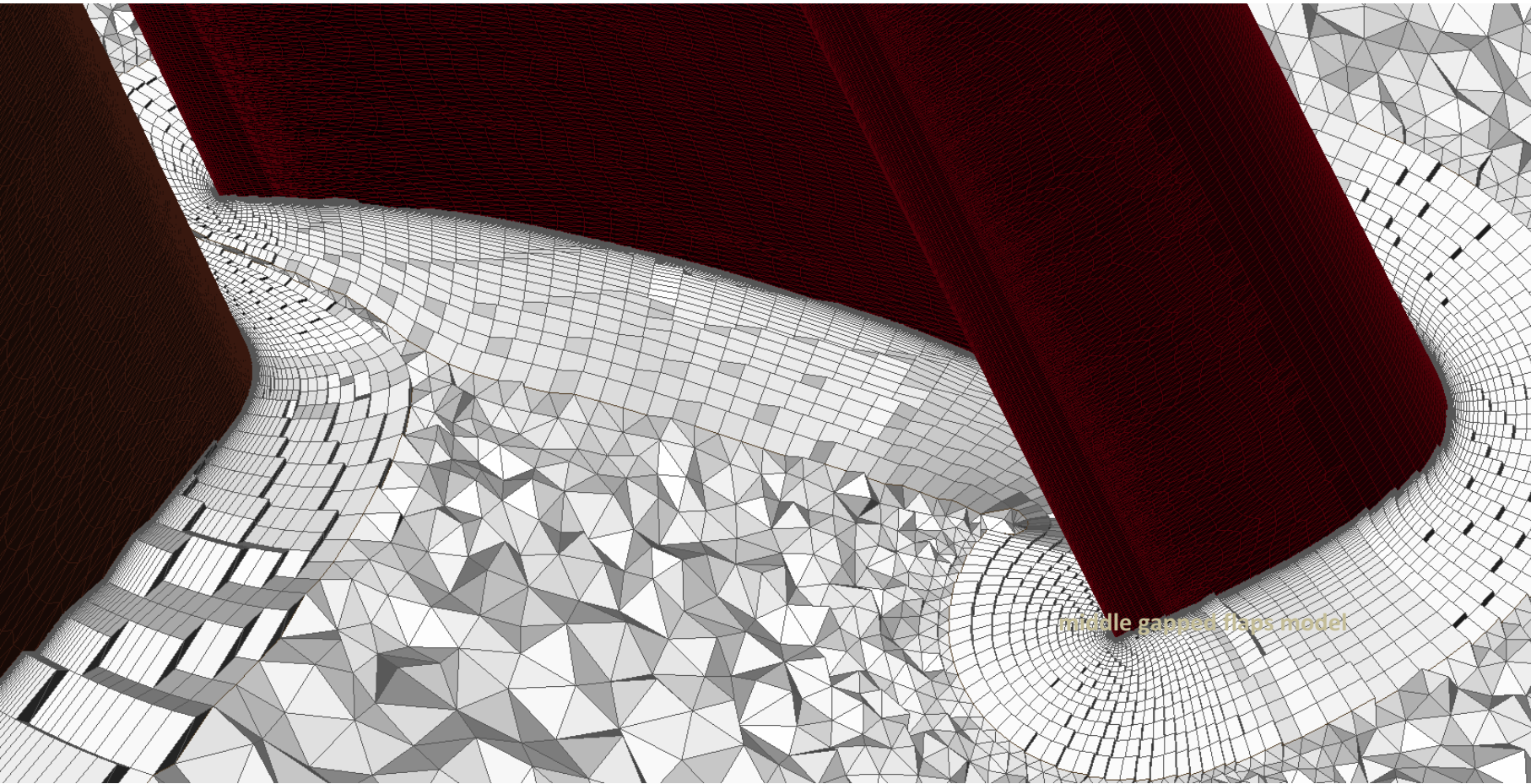
	Coarse gapped flaps	Medium gapped flaps	Medium sealed flaps	Fine gapped flaps
Surface mesh size (millions)	1.8	2.4	2.3	2.8
Volume mesh size (millions)	89	147	143	237
Trailing edge rows of elements	4	6	6	8
Number of Layers	Wing:40 Fuselage:45	Wing:45 Fuselage:57	Wing:45 Fuselage:57	Wing:65 Fuselage:84
Layers growth	1.25	1.16	1.16	1.1
Layers first height (inches)	0.000787	0.000787	0.000787	0.000787

CRM close up near slat lower side



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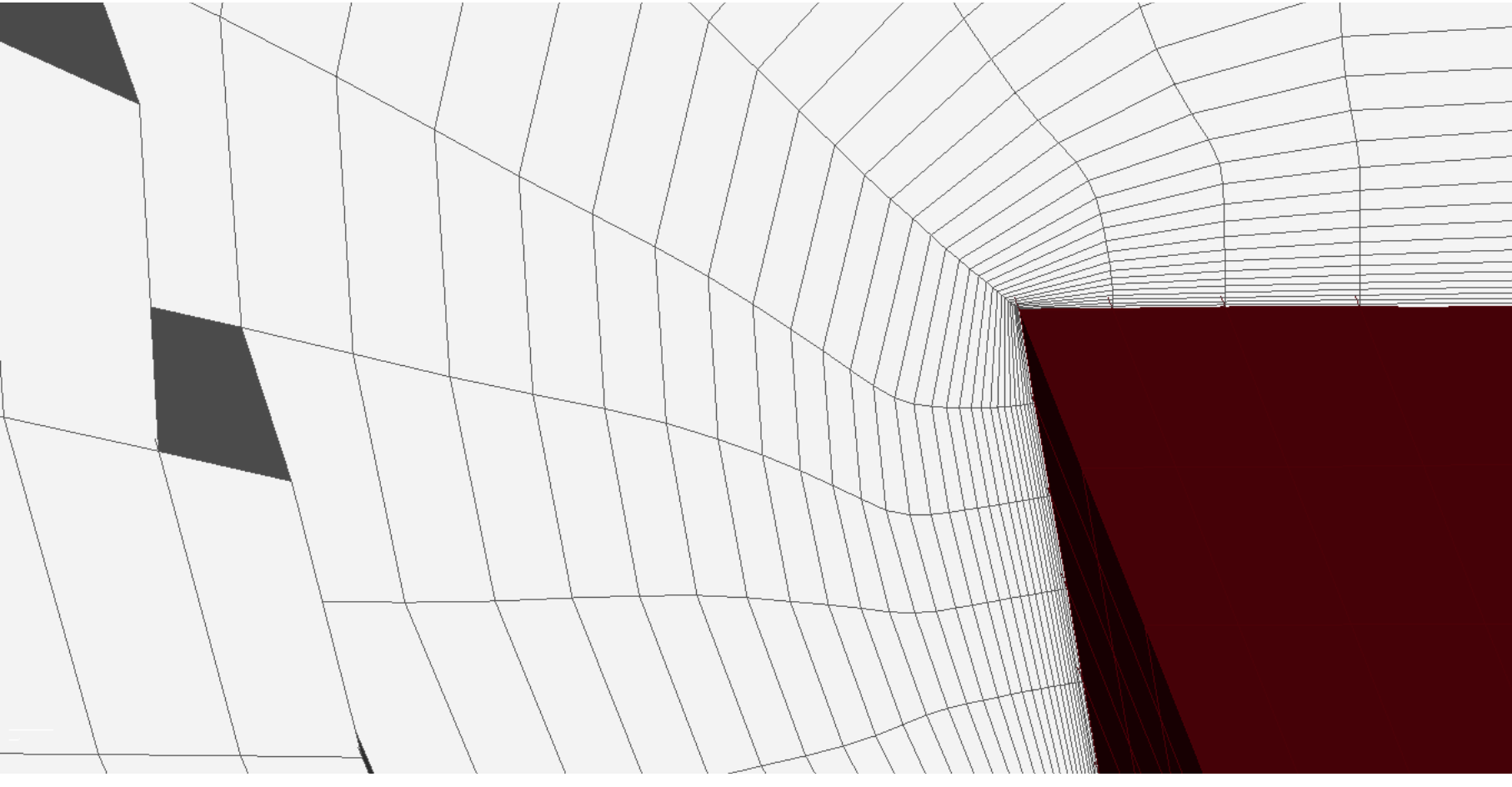
CRM imposed orthogonality of layers near the wall – will reduce OpenFOAM wall-distance problem



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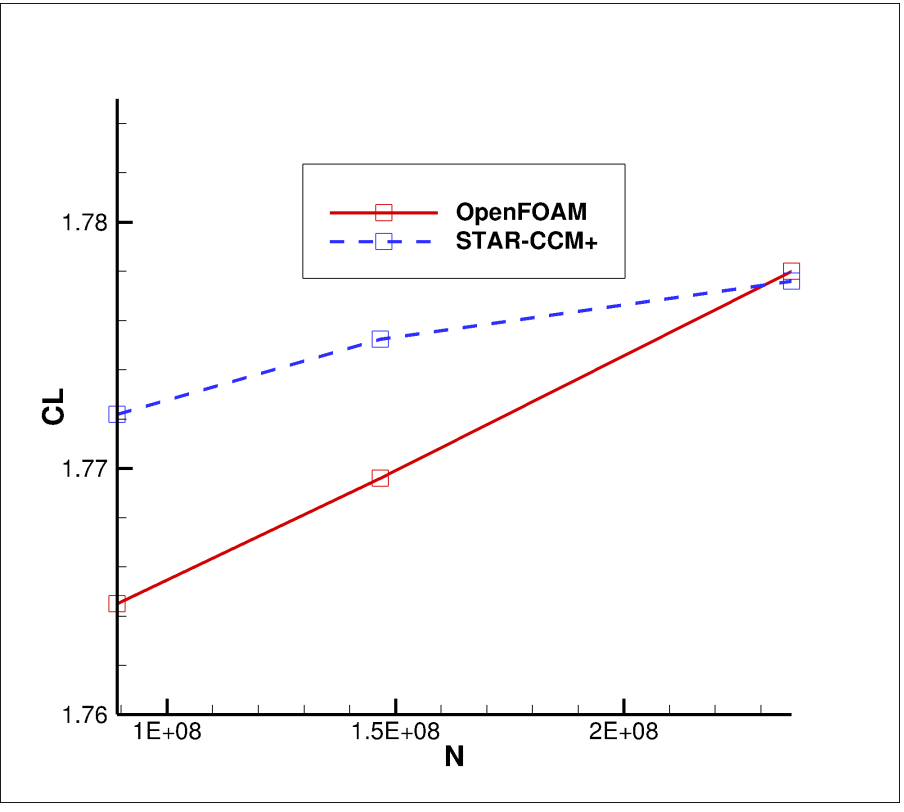
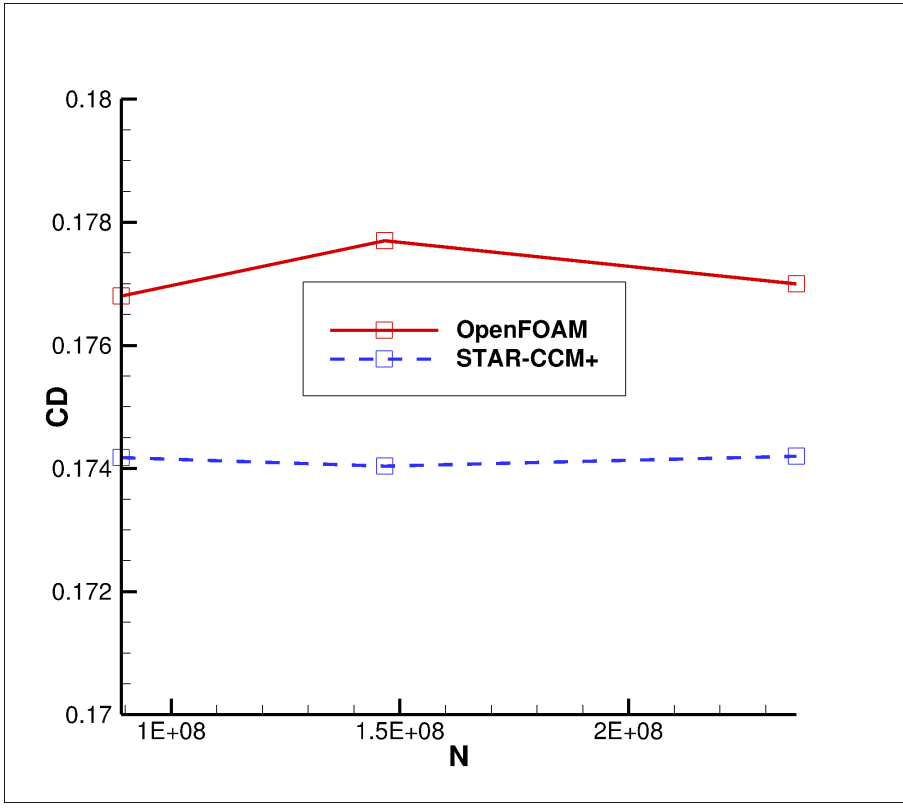
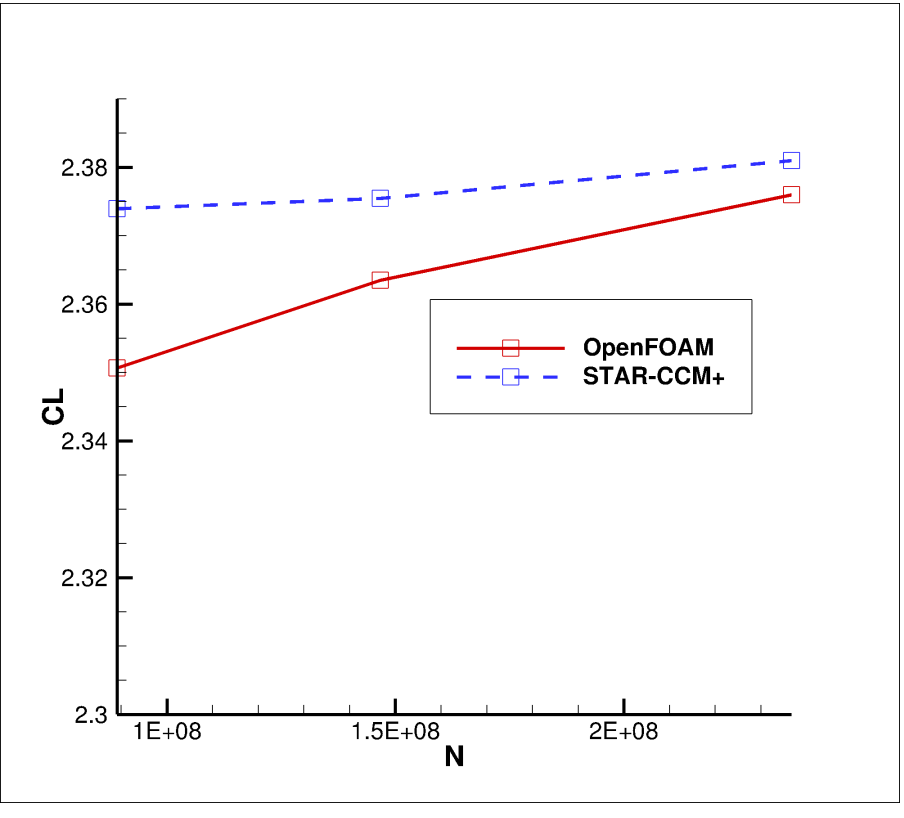
HL-CRM Results

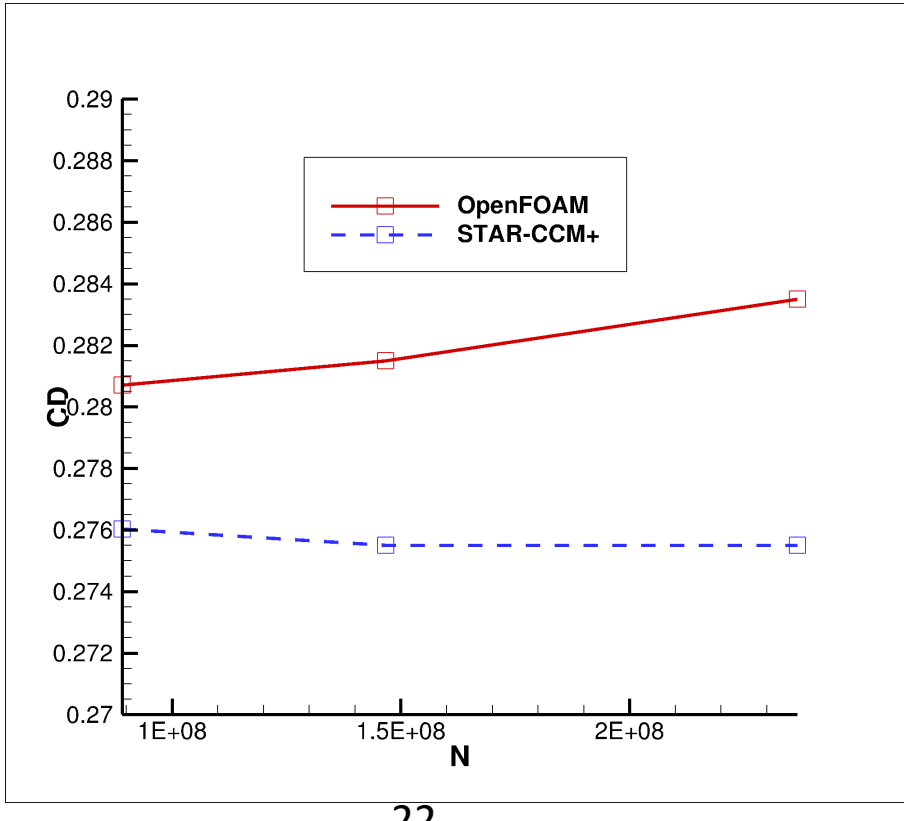
- Not reached mesh convergence by finest grid (236 million cells)
- Codes converge on the lift (<0.01%), constant 1.1% offset on the drag
- Suspected wall-distance related error for OpenFOAM (same drag as NACA airfoil)





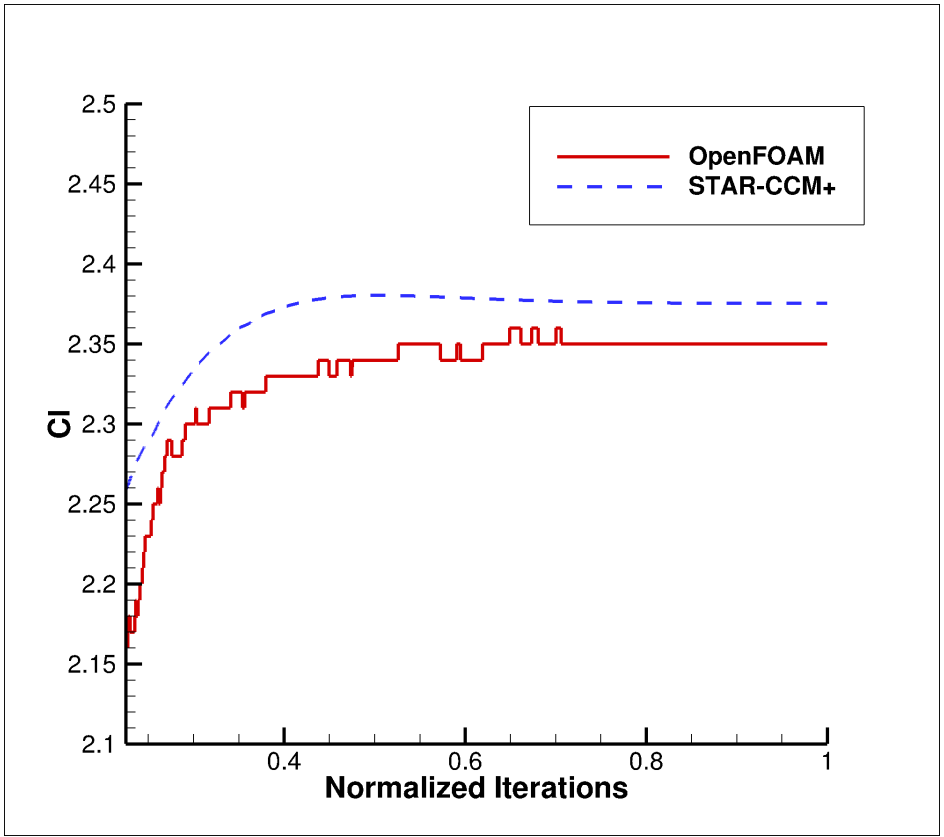
- Similar story at 16°
- <0.5% offset in Lift, 2% offset in Drag



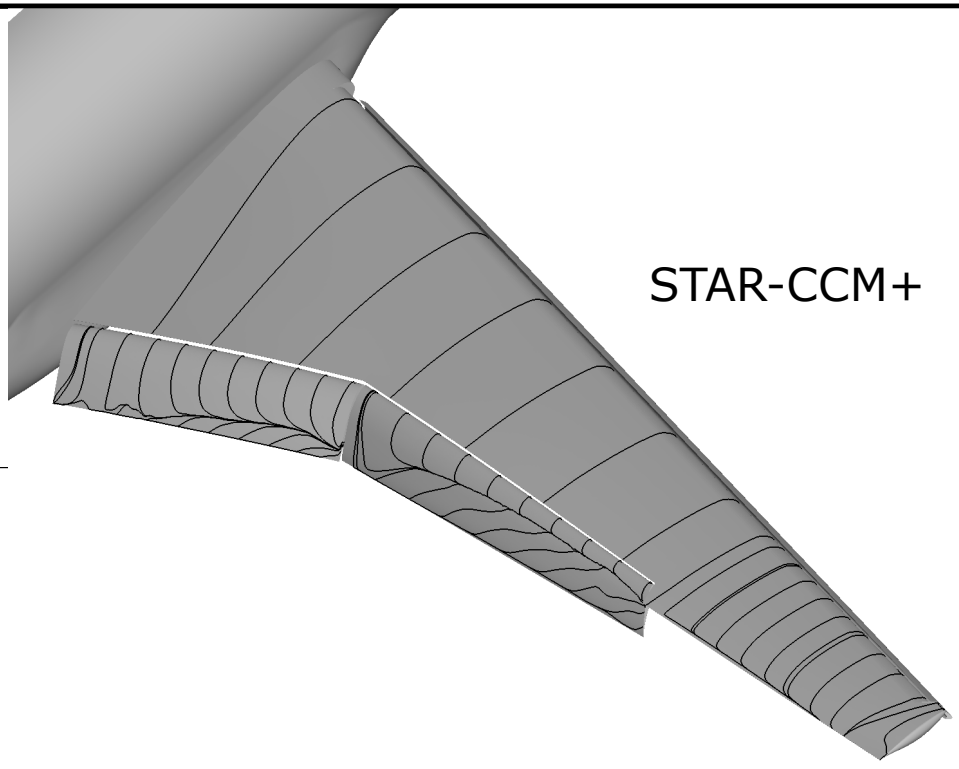


Force convergence

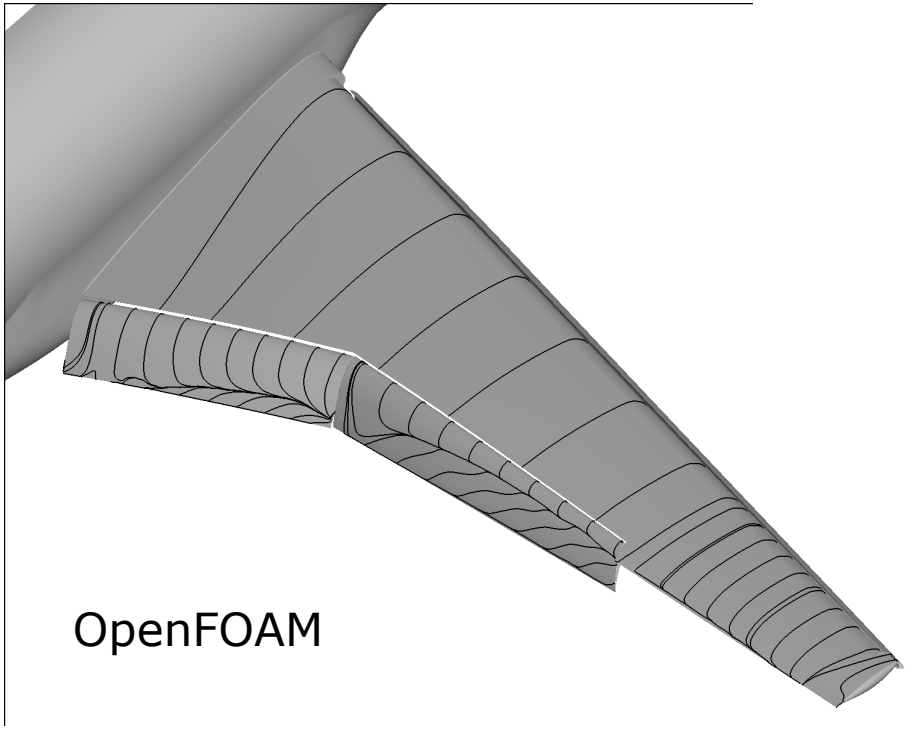
- Convergence for medium grid 16^{o} is good for a complex geometry/mesh
- OpenFOAM less smooth than STAR-CCM+ likely down to stabilize tools in STAR-CCM+
- STAR-CCM+ could run higher CFL (5-10) than OpenFOAM (~1) – thus STAR = 30-50k iterations, OpenFOAM – 100-150k iterations



HL-CRM 8º



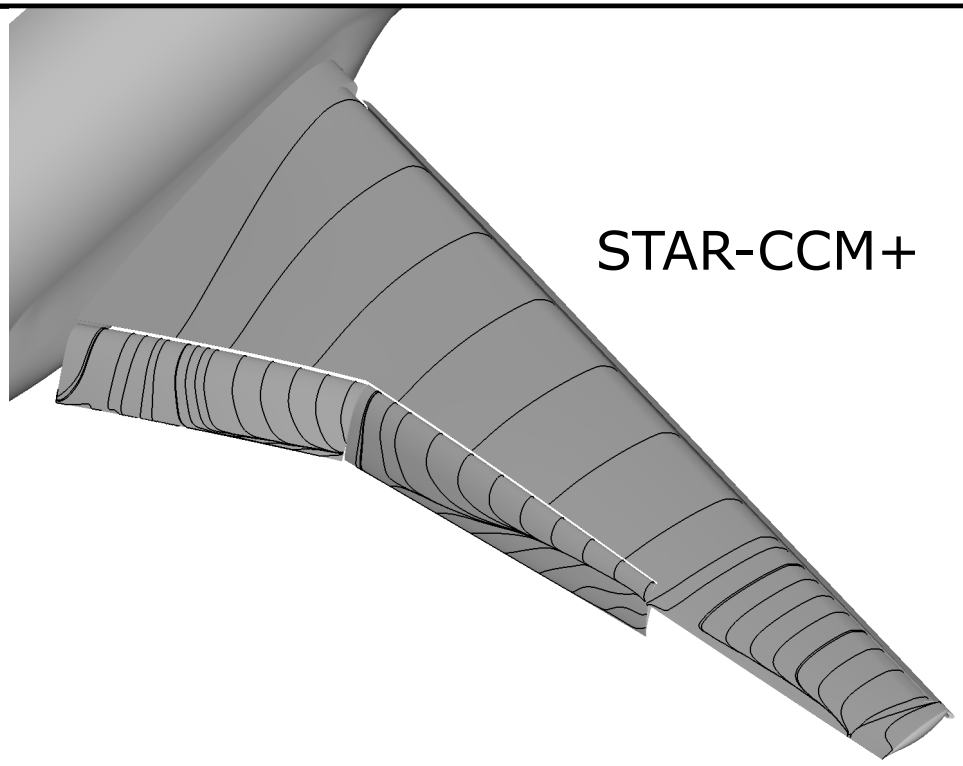
STAR-CCM+



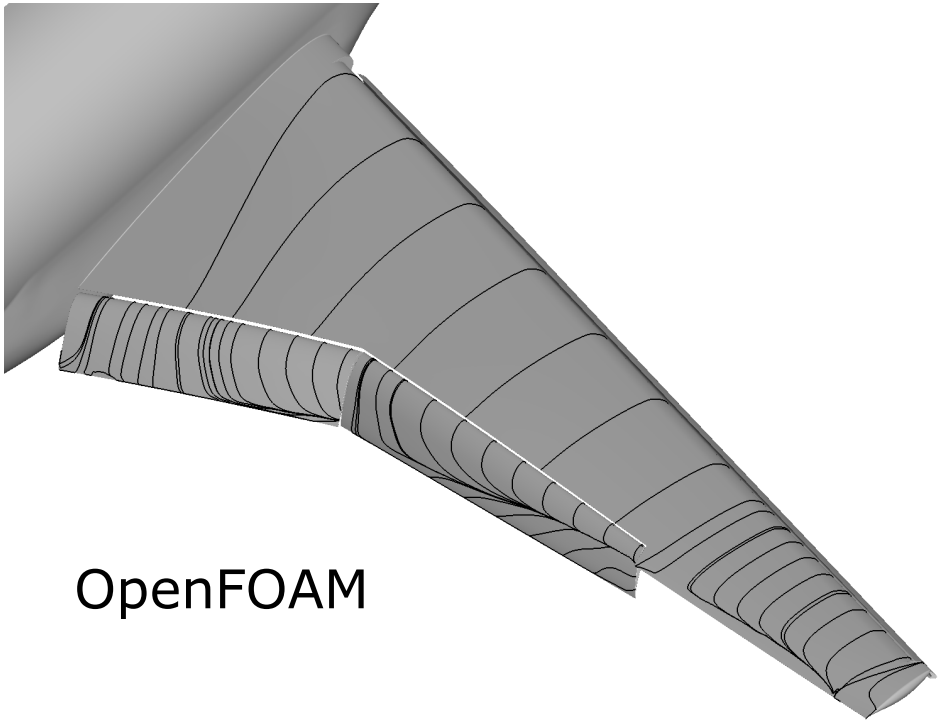
OpenFOAM

- **Inboard & Outboard flap separation**

HL-CRM 16°



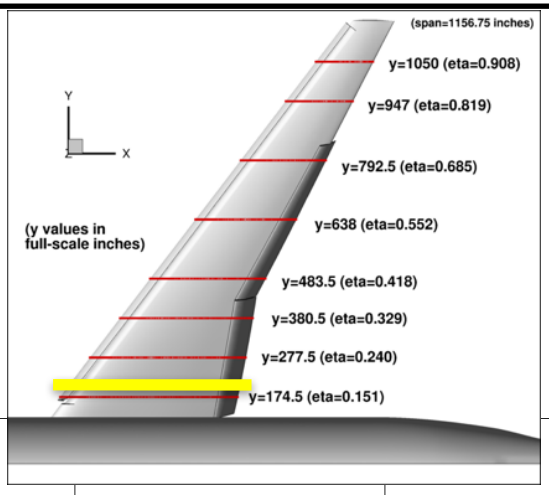
STAR-CCM+

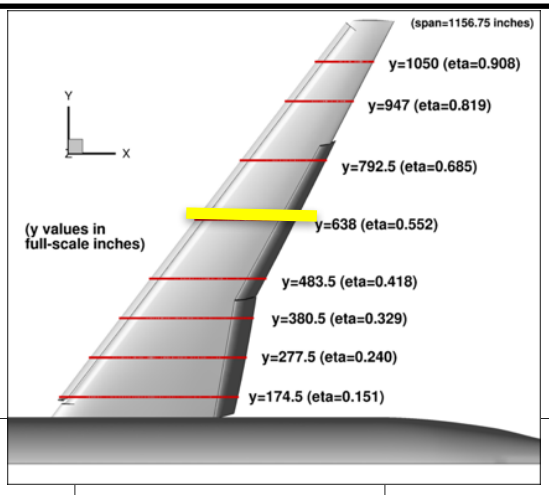


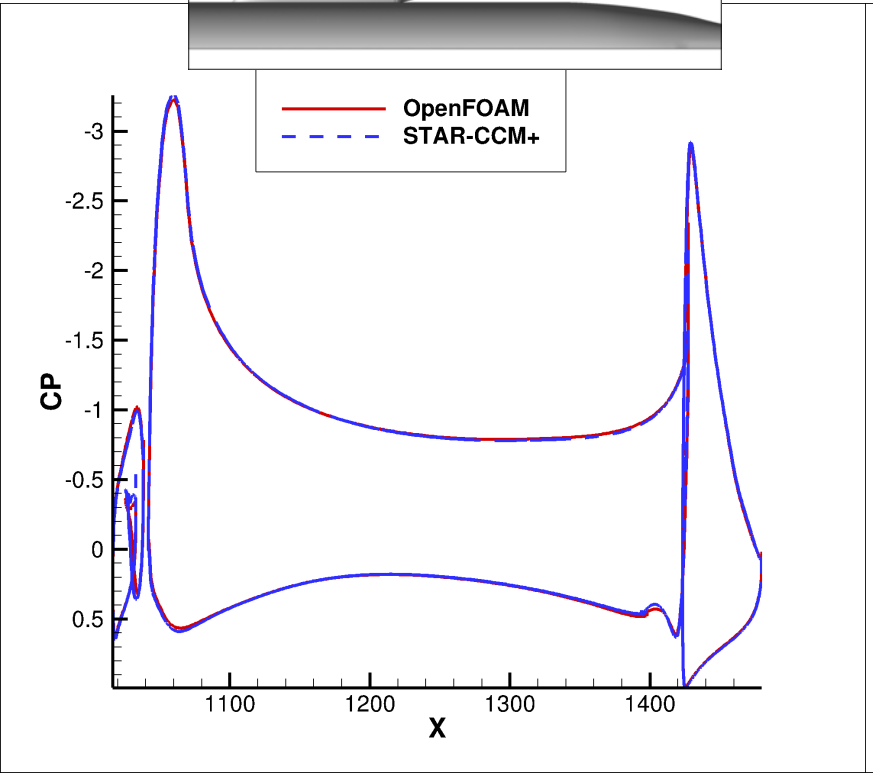
OpenFOAM

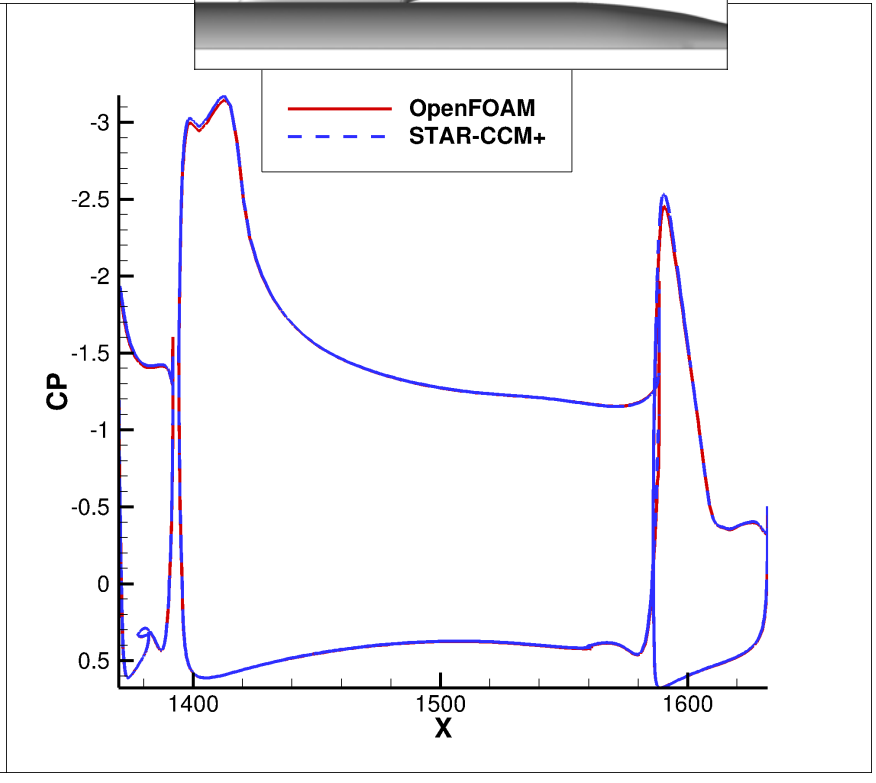
- **Outboard flap separation only**

HL-CRM 8º – eta 151,552

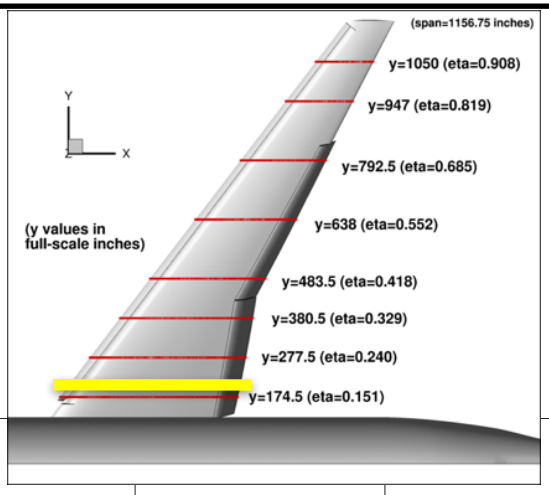




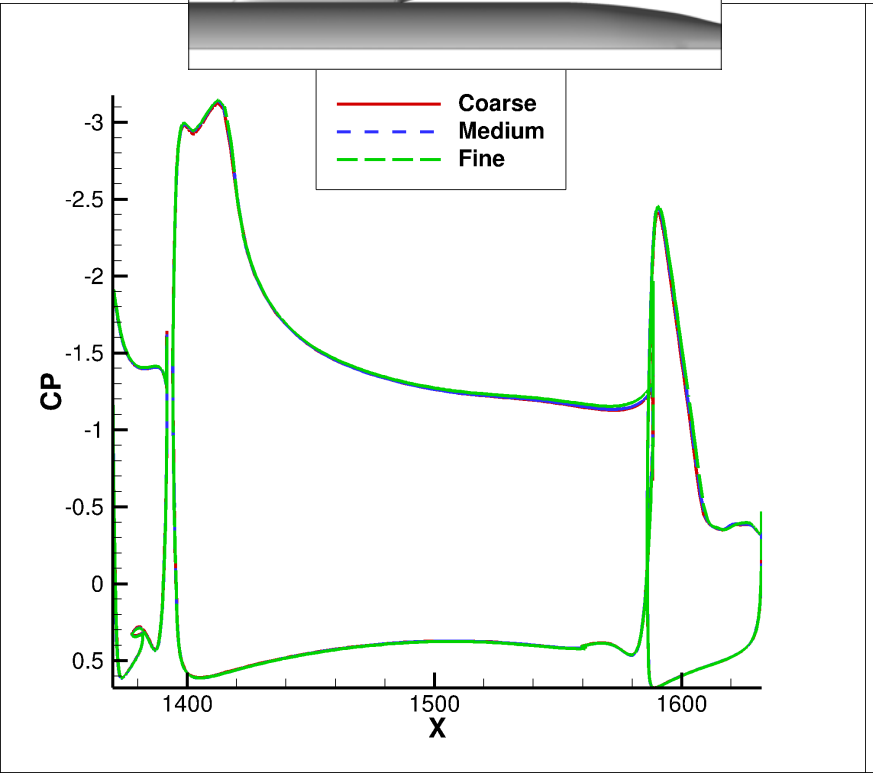


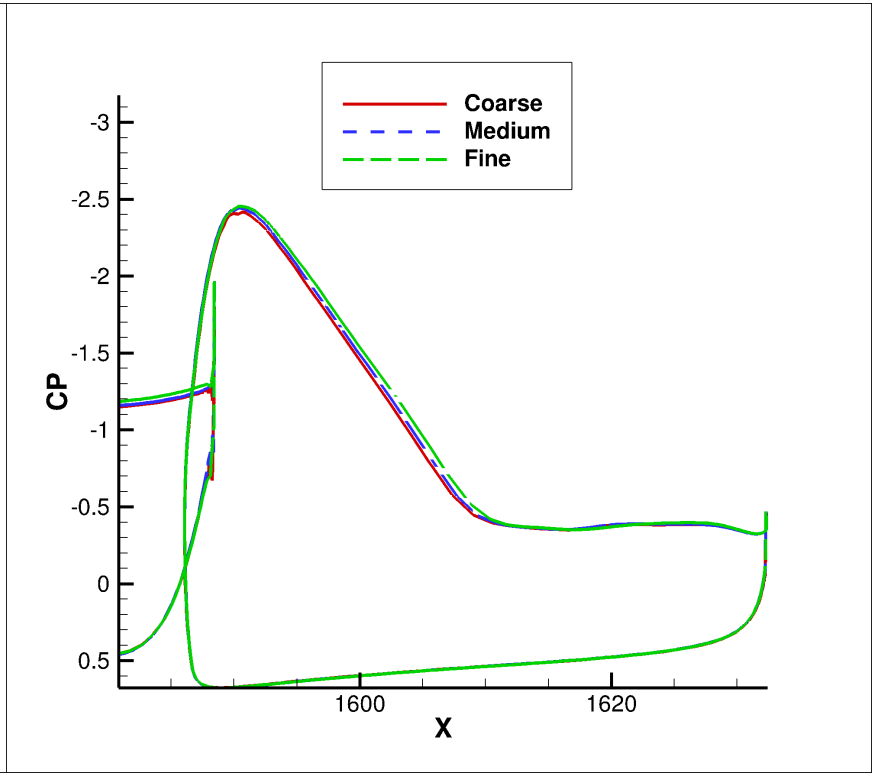


HL-CRM 8º – eta 151

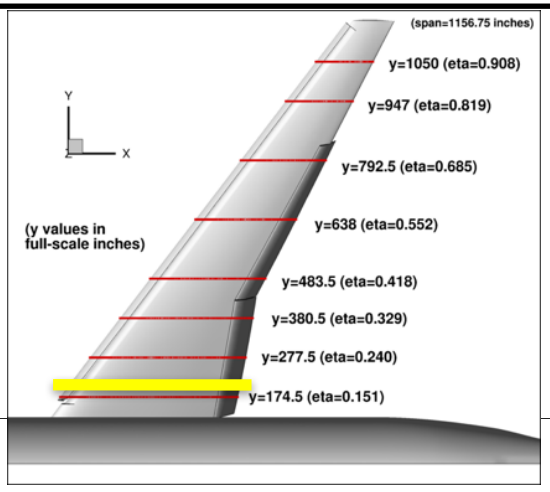


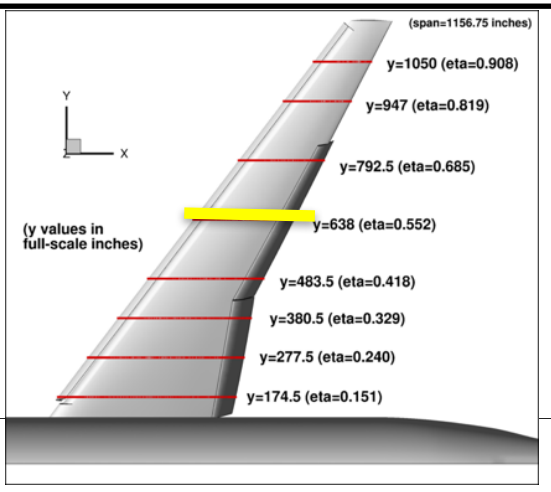
Slight changes with grid refinement

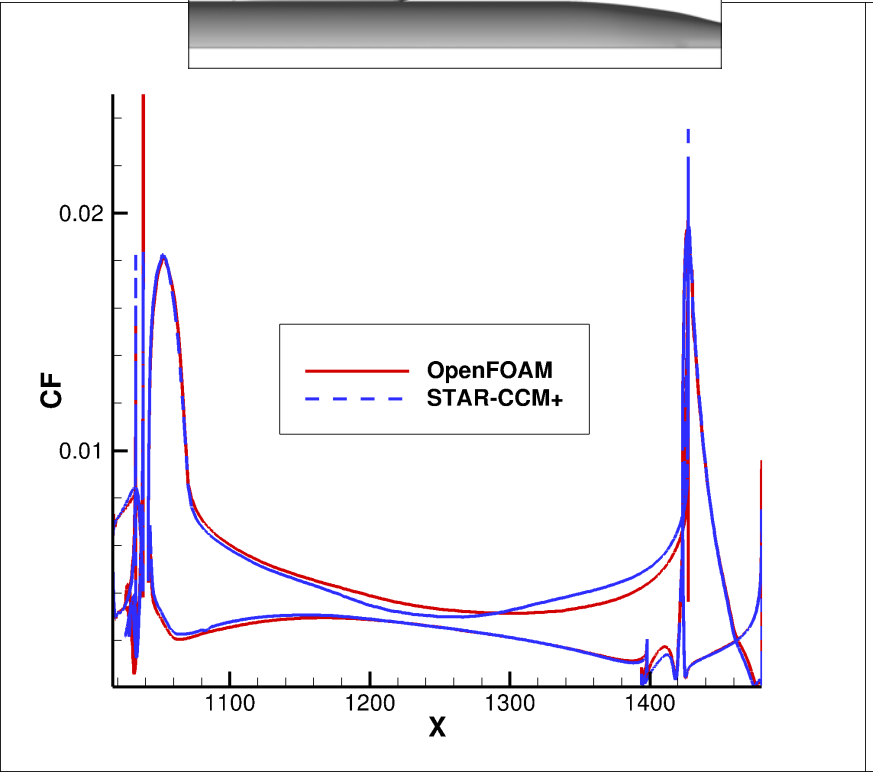


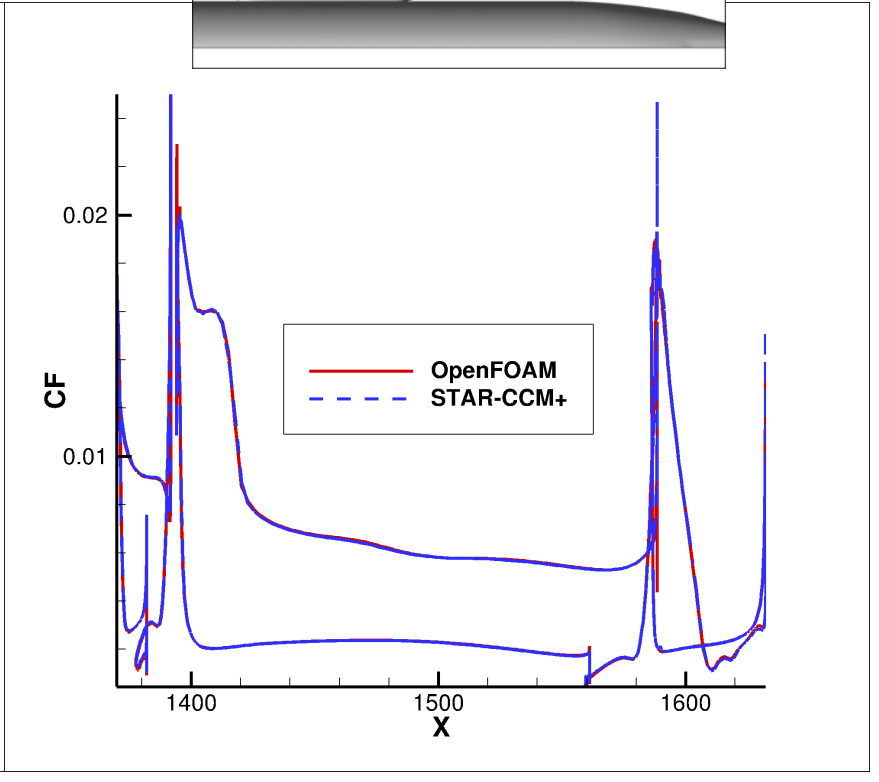


HL-CRM 8º – eta 151,552 - C_f

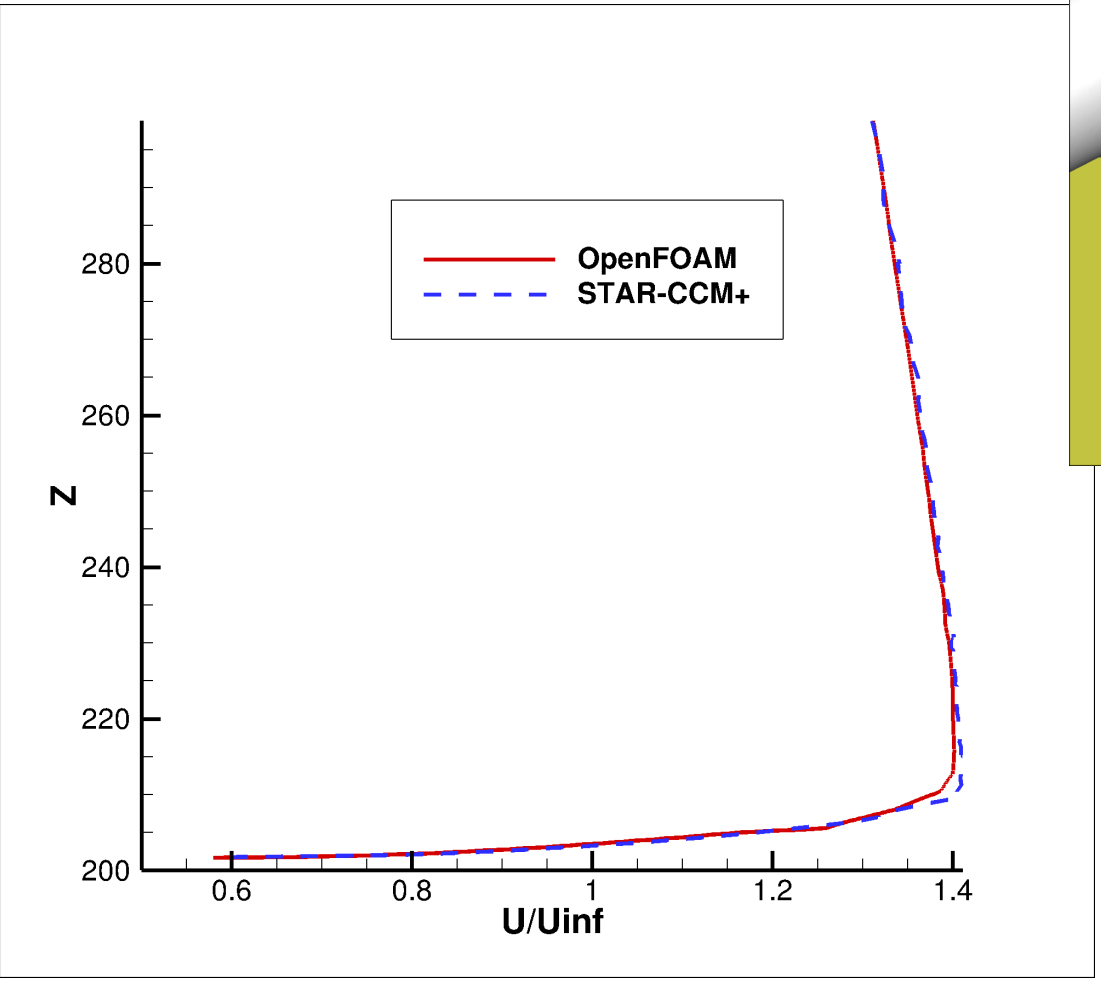


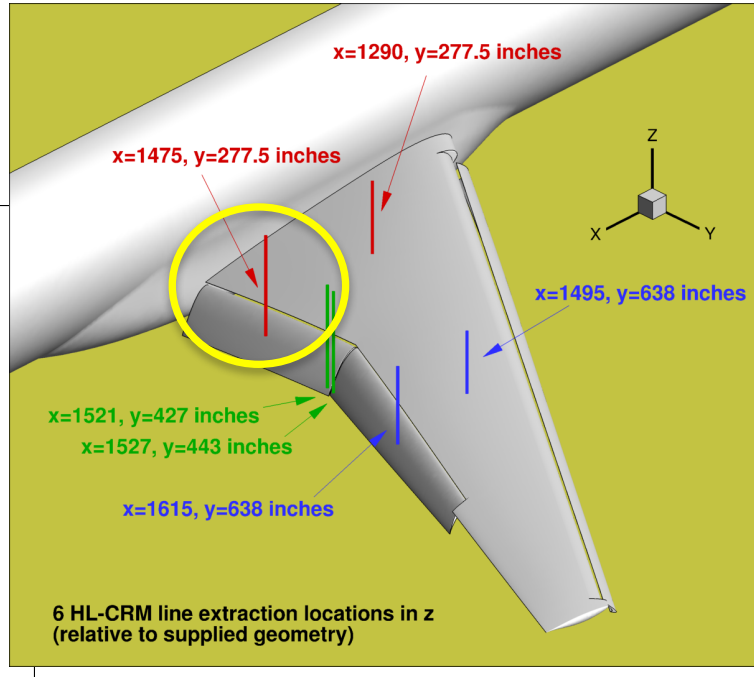




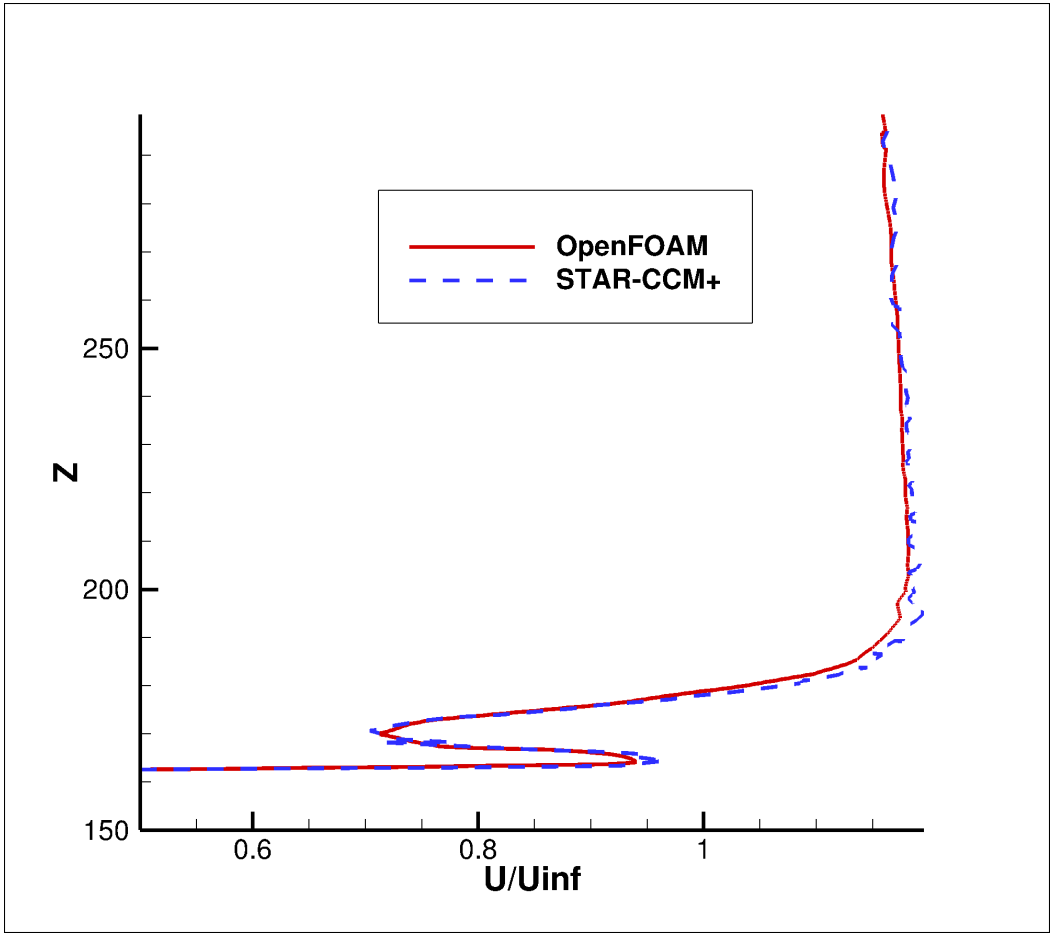


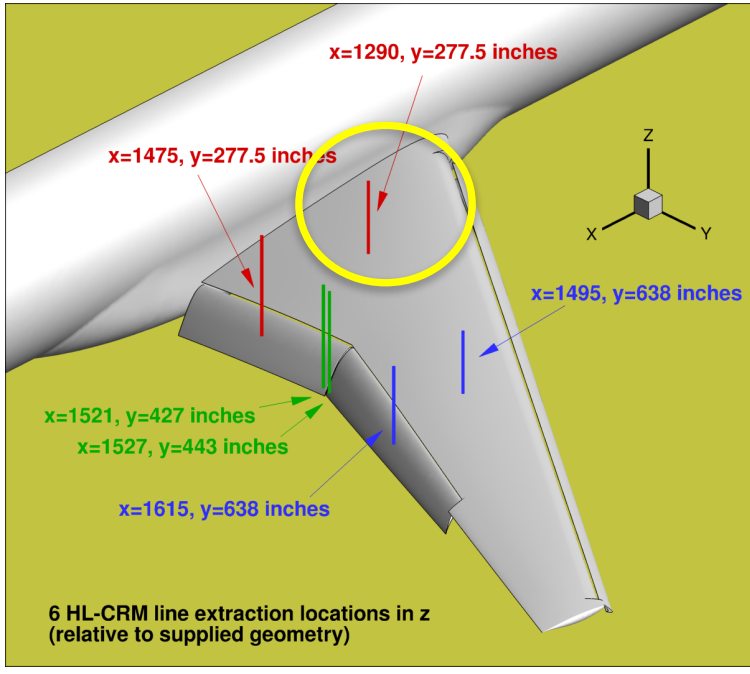
HL-CRM 16° – Velocity profiles





HL-CRM 16º – Velocity profiles





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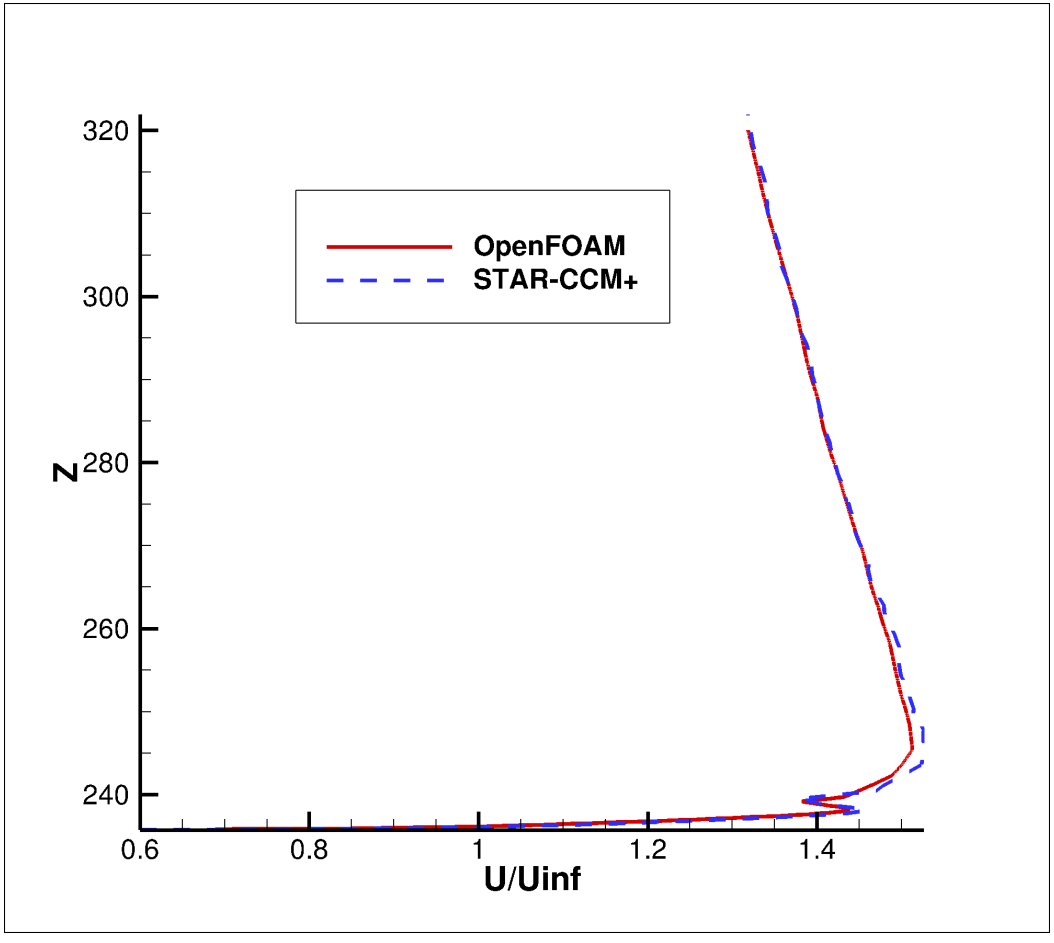
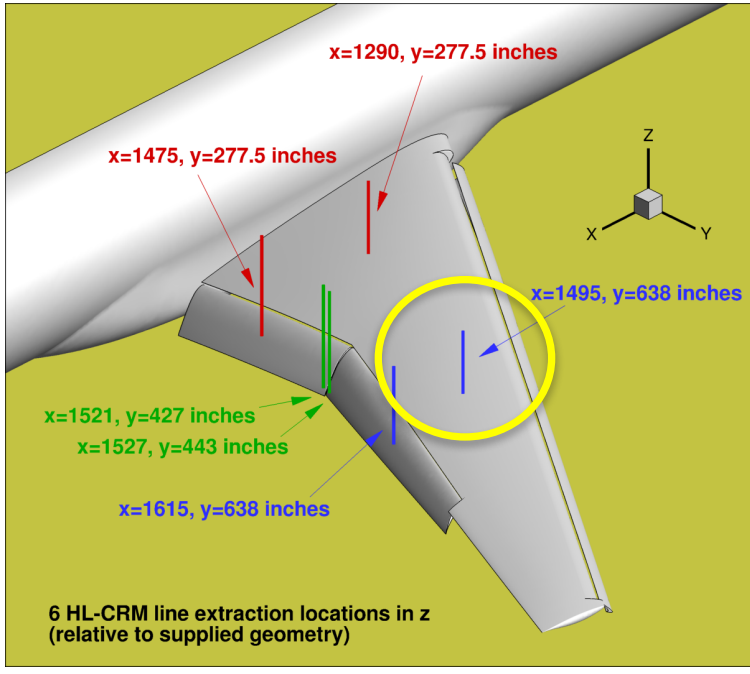
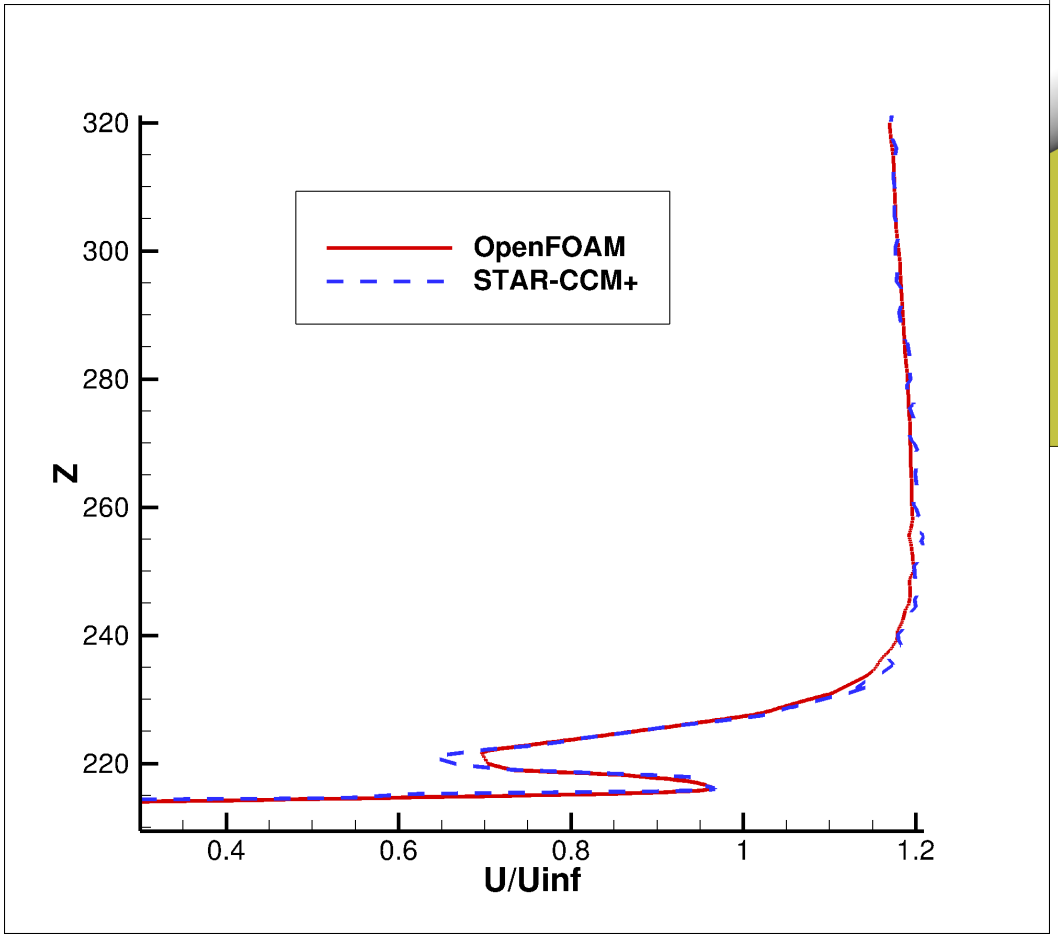
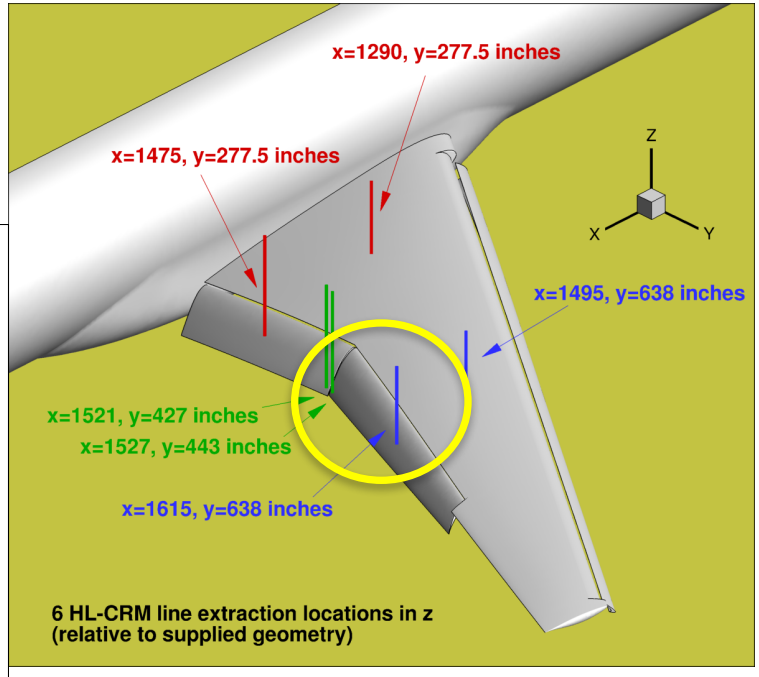




HL-CRM 16º – Velocity profiles





HL-CRM conclusions

- < 0.5% agreement between STAR-CCM+ and OpenFOAM on Lift, ~1-2% different in Drag
- Visually very similar flow structure and Cp distribution
- Outboard flap separation and slightly inboard flap for 8 degrees
- Only outboard flap separation at 16 degrees

JSM Results

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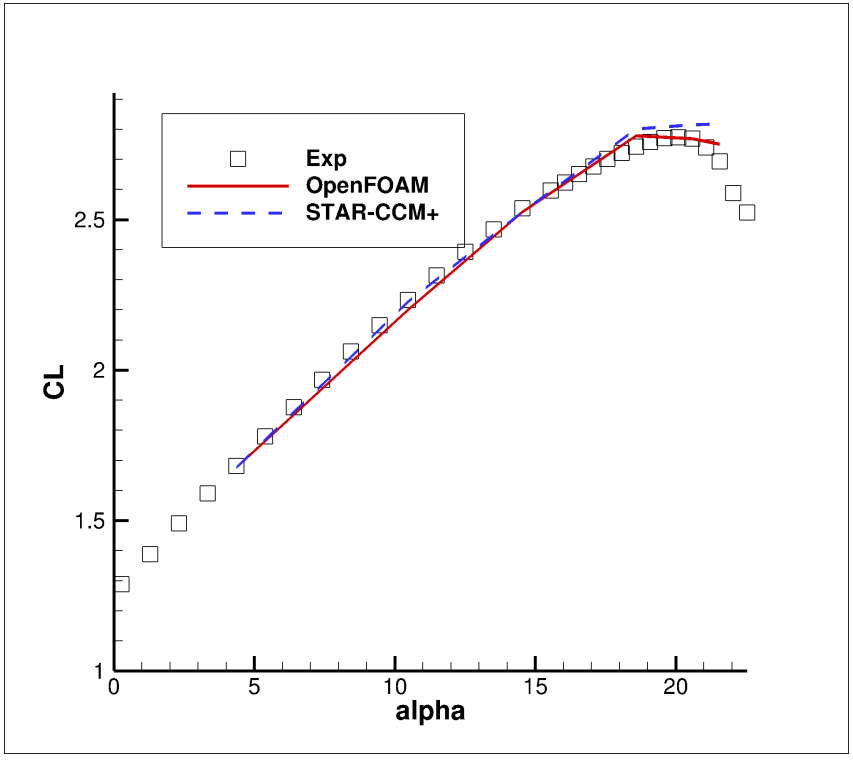
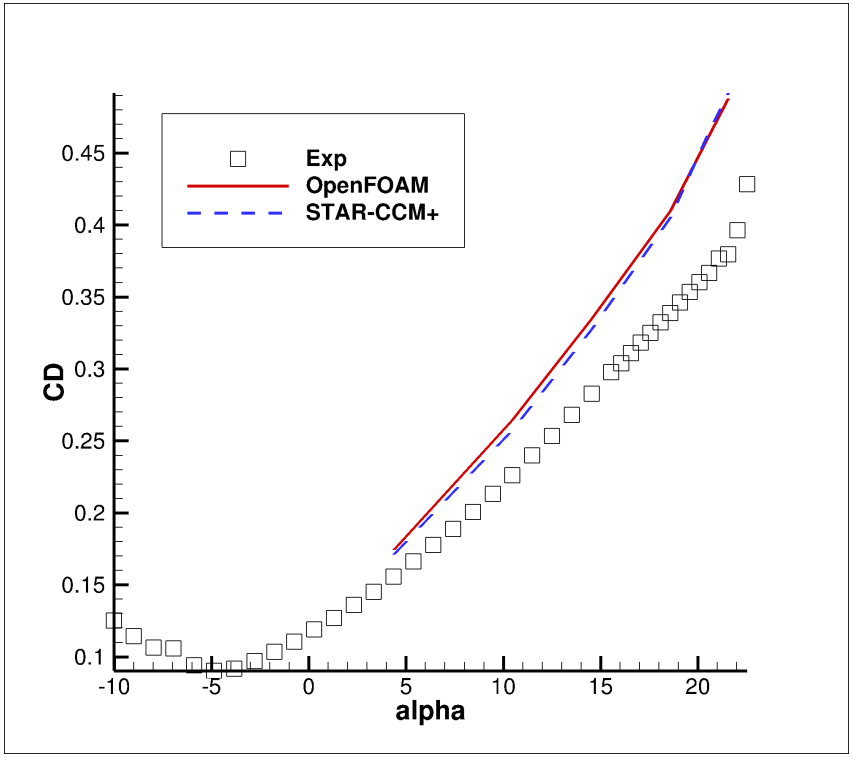
Same approach take as to HL-CRM. Additional fine mesh created but not run

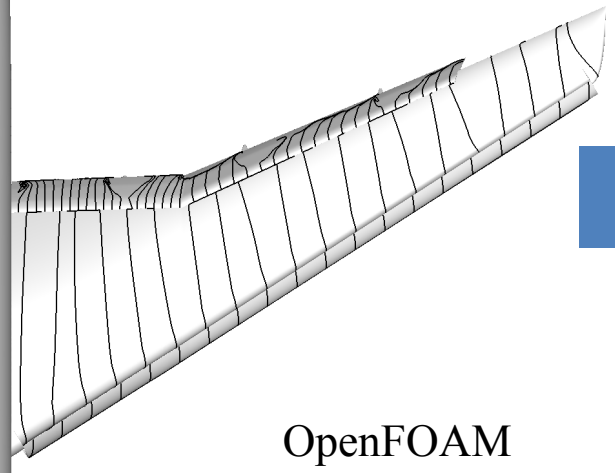
	Medium Case 01 (w/o nacelle)	Medium Case 02 (with nacelle)
Surface mesh size (millions)	1.7	1.8
Volume mesh size (millions)	109	120
Trailing edge rows of elements	8	8
Number of Layers	Wing:49 Fuselage:57	Wing:49 Fuselage:57
Layers growth	1.16	1.16
Layers first height (mm)	0.0015	0.0015



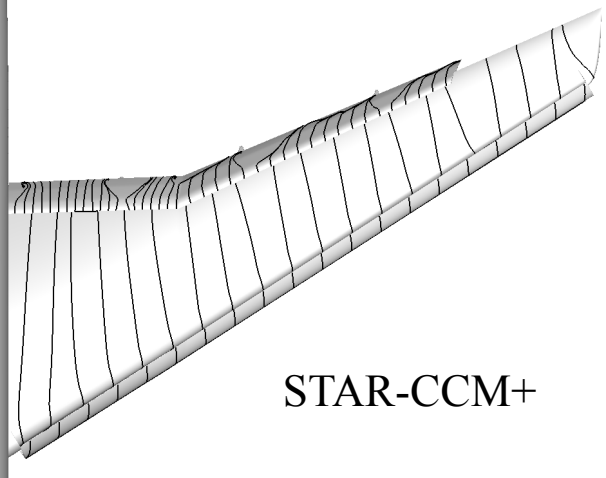


- Average difference between OpenFOAM & STAR-CCM+ = 1.0% for Lift and 1.1% for Drag
- Max difference is **2.3%**

JSM no-nacelle 4.36°

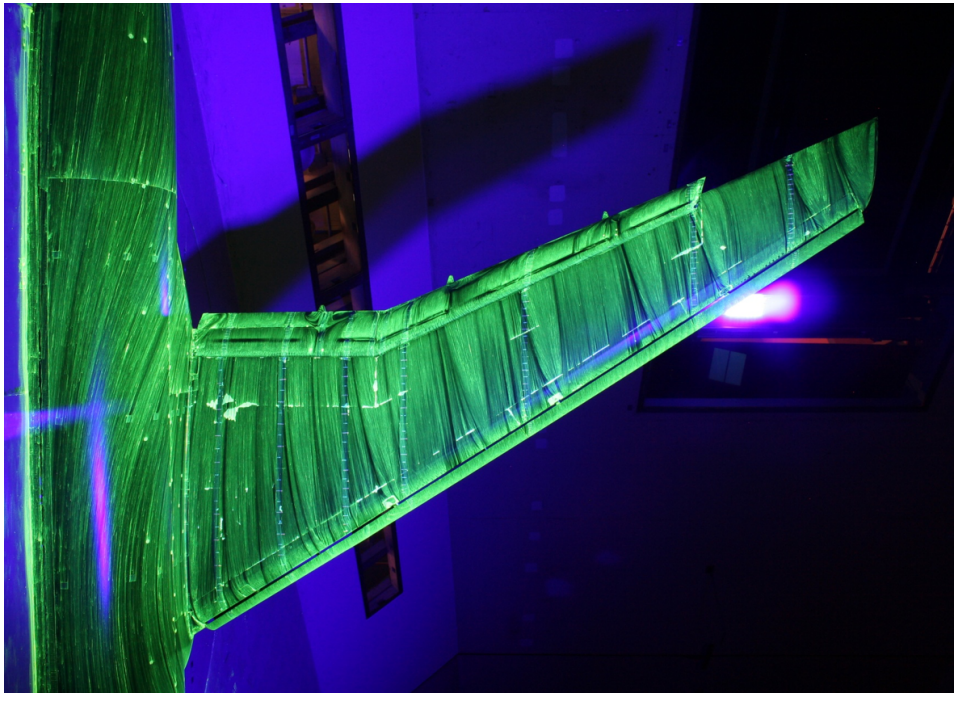


OpenFOAM

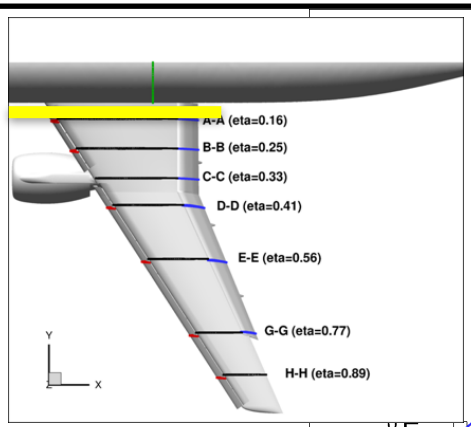


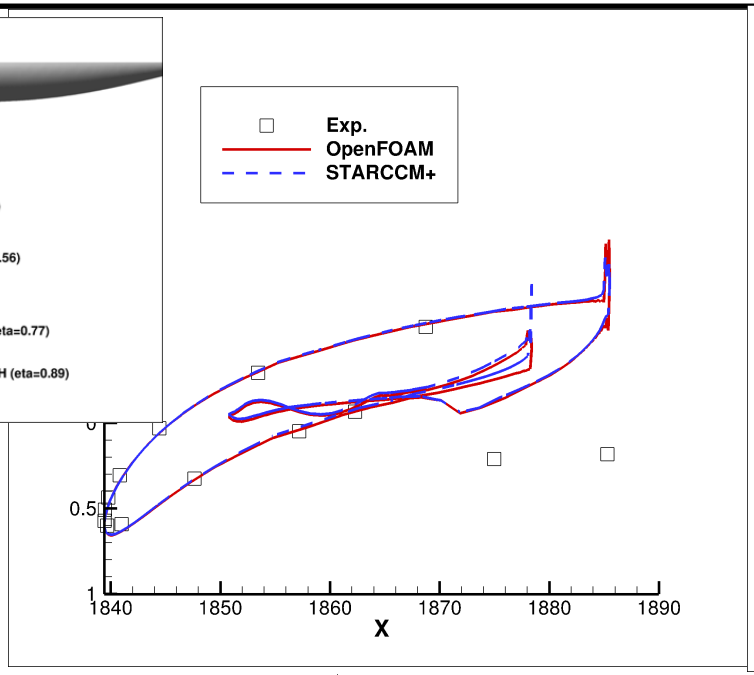
STAR-CCM+

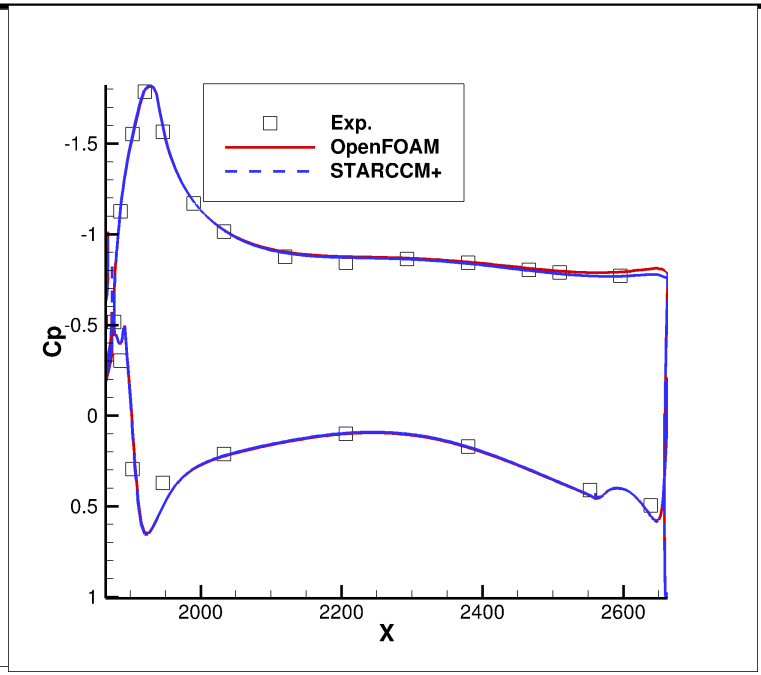
Good agreement between CFD and Exp.

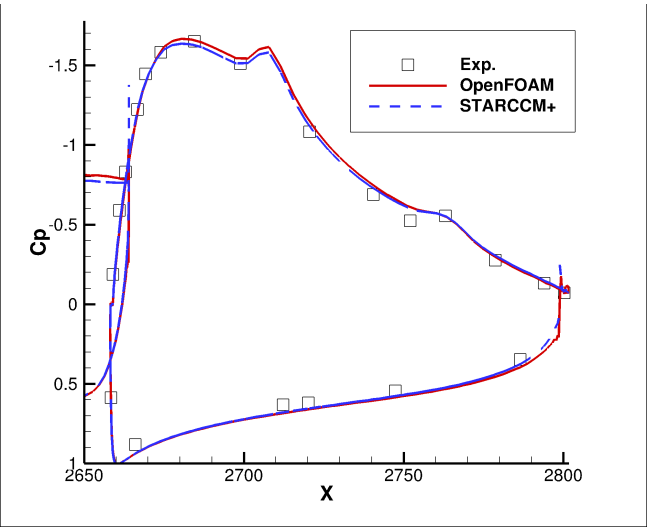


JSM no-nacelle 4.36° – A-A



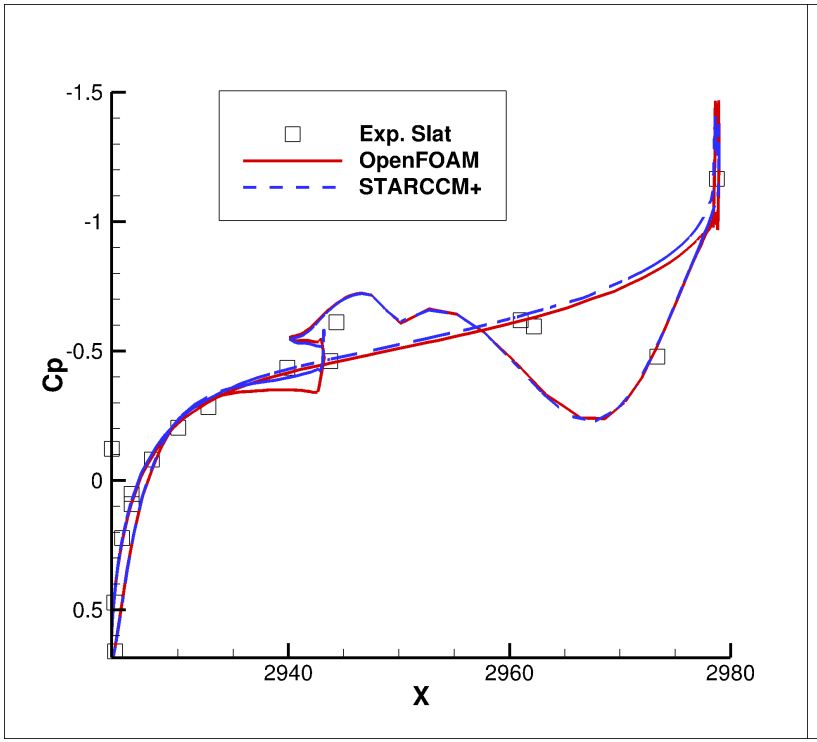


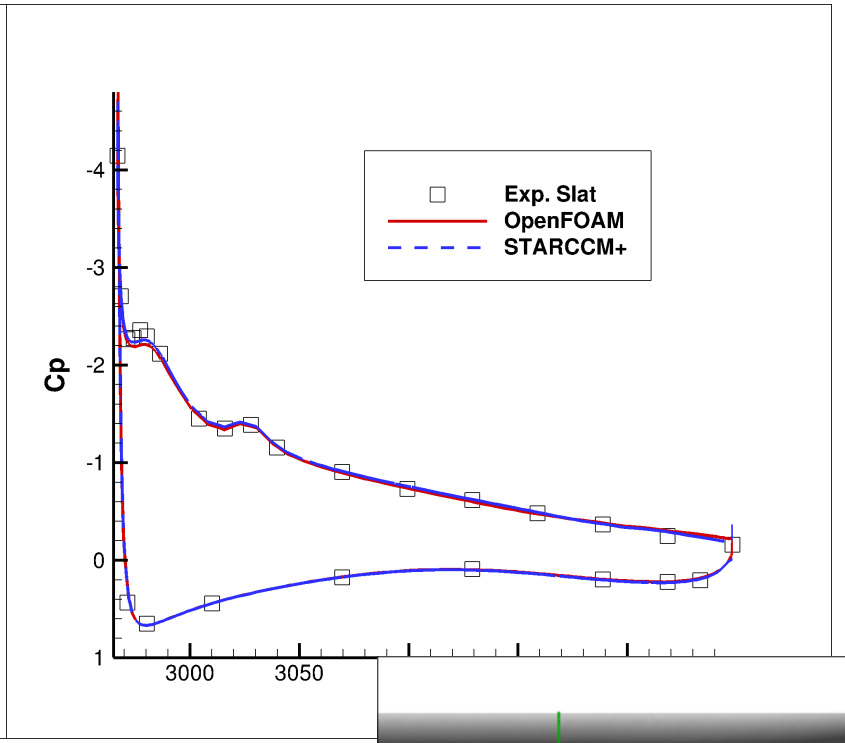




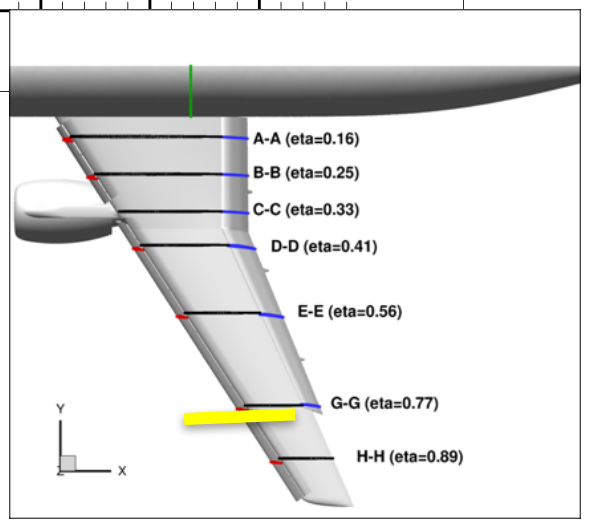
- Wing & flap agree well
- Slat looks like exp. error perhaps?

JSM no-nacelle 4.36º – H-H

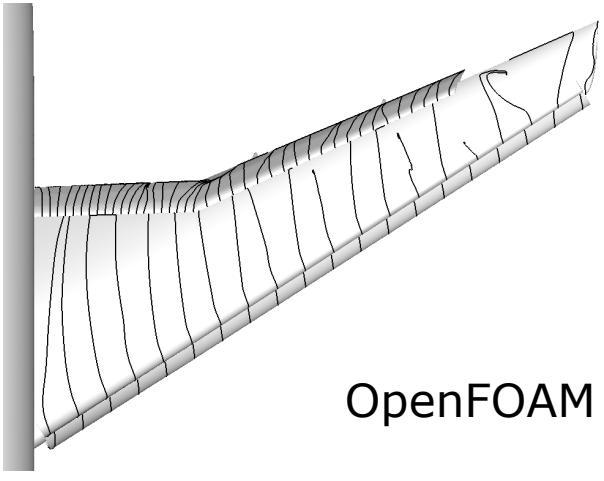




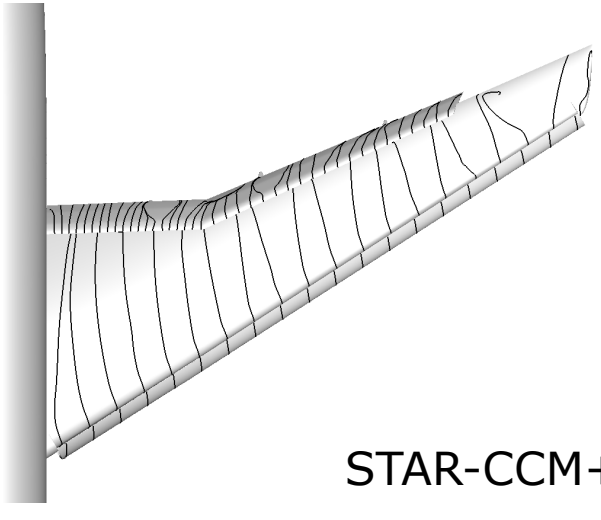
- Both codes agree with experimental data



JSM no-nacelle 18.58°

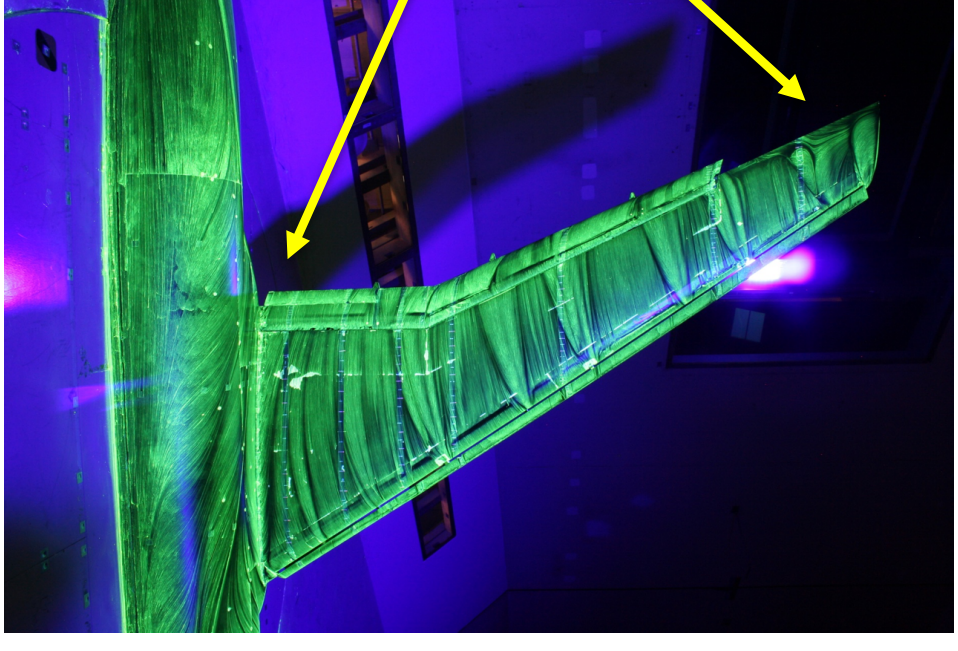


OpenFOAM

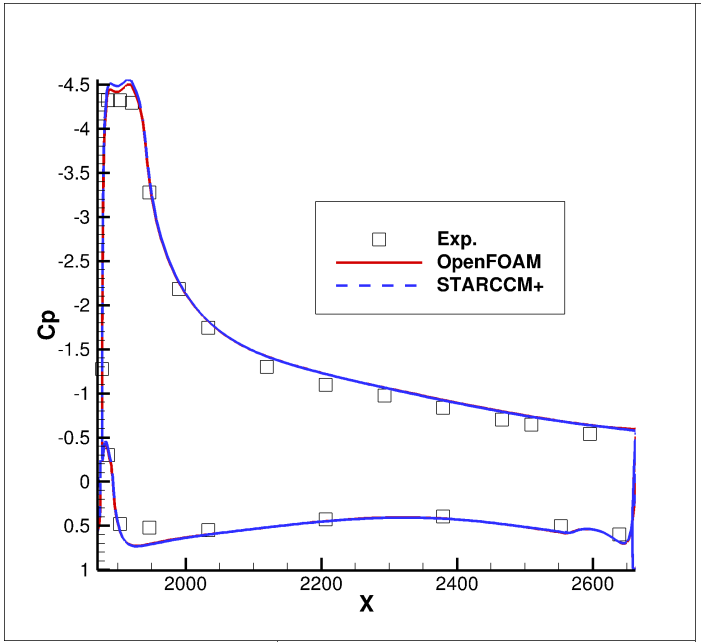


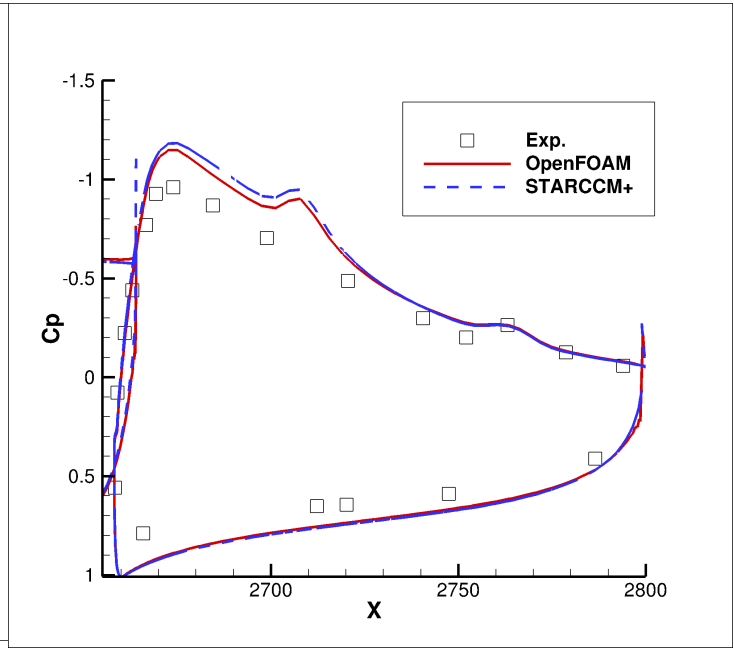
STAR-CCM+

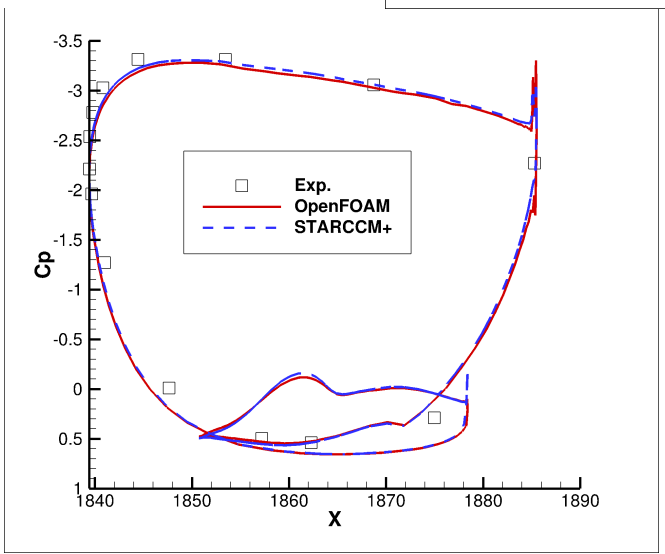
- Missing the start of the in-board separation
- Slight over-prediction of outboard losses

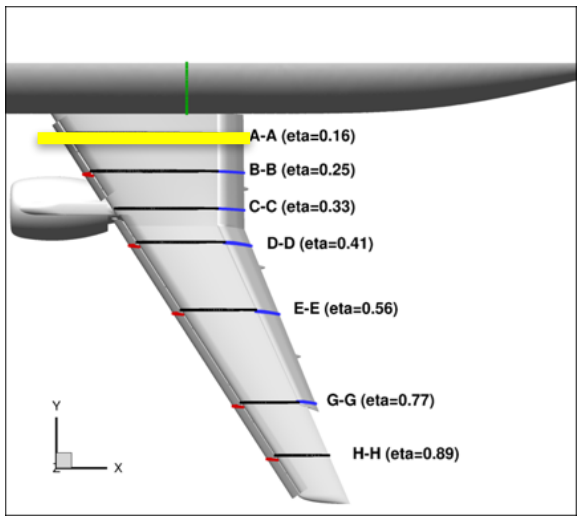


JSM no-nacelle 18.58º – A-A

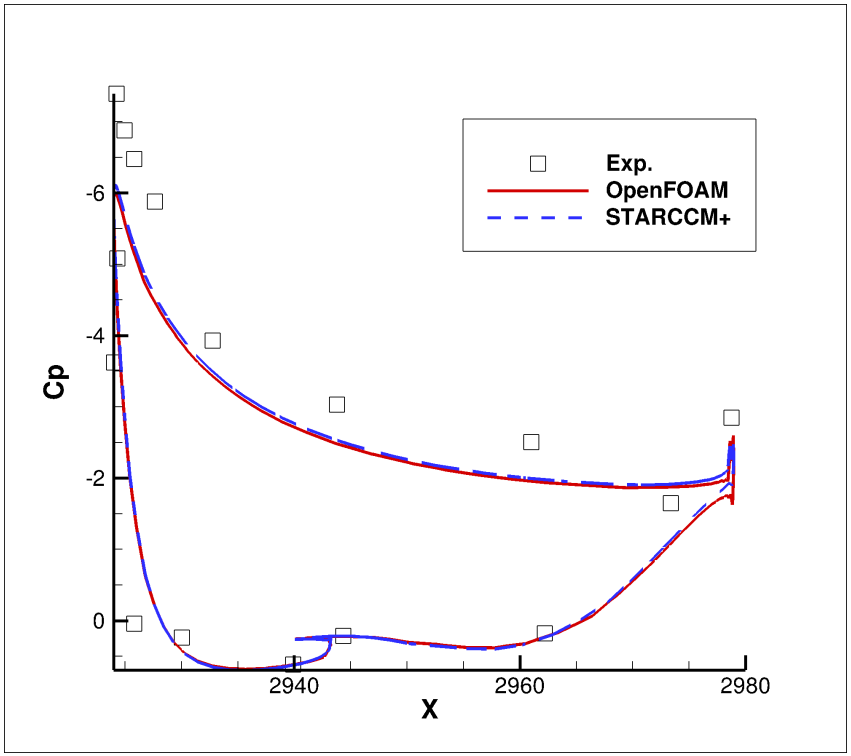


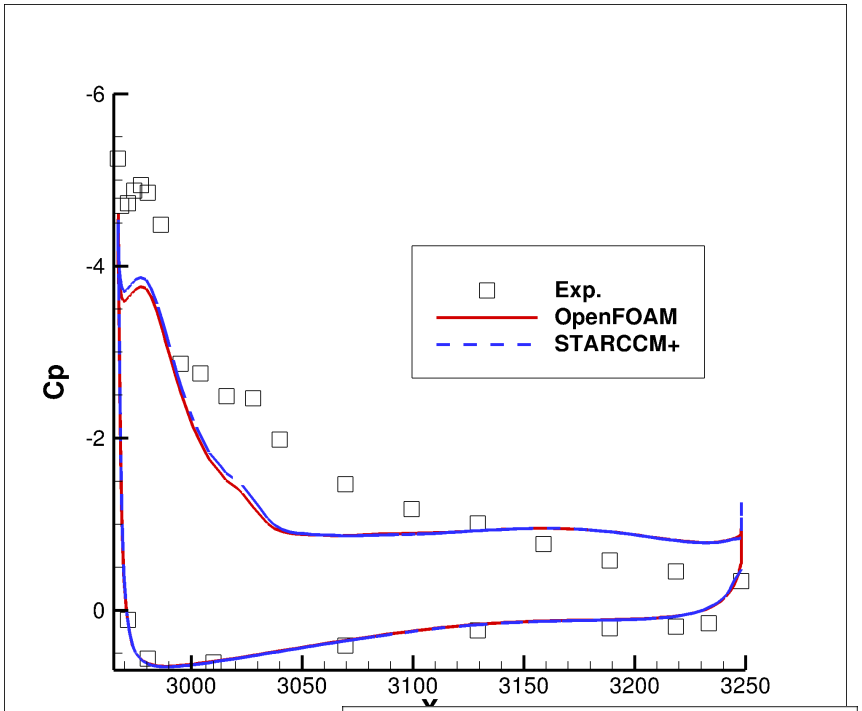


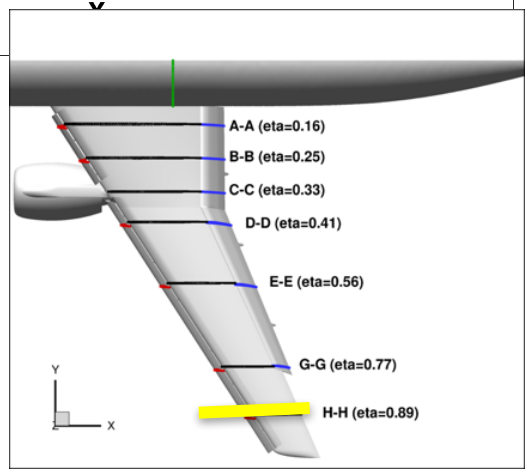




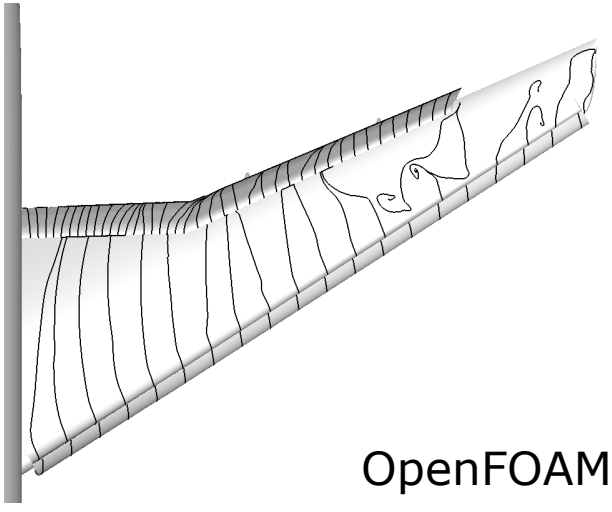
JSM no-nacelle 18.58º – H-H



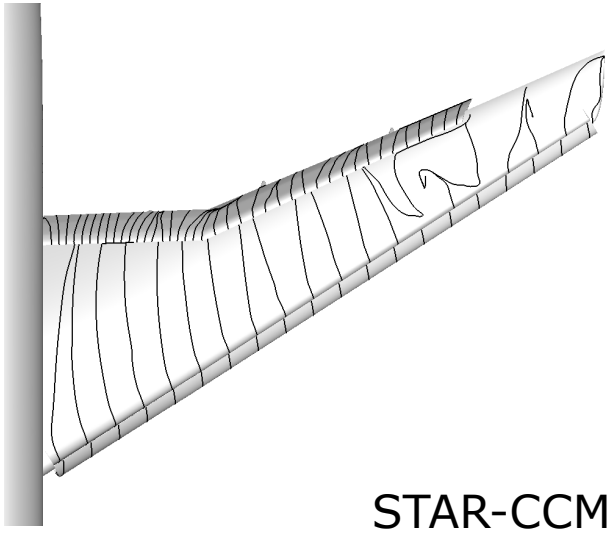




JSM no-nacelle 21.57°

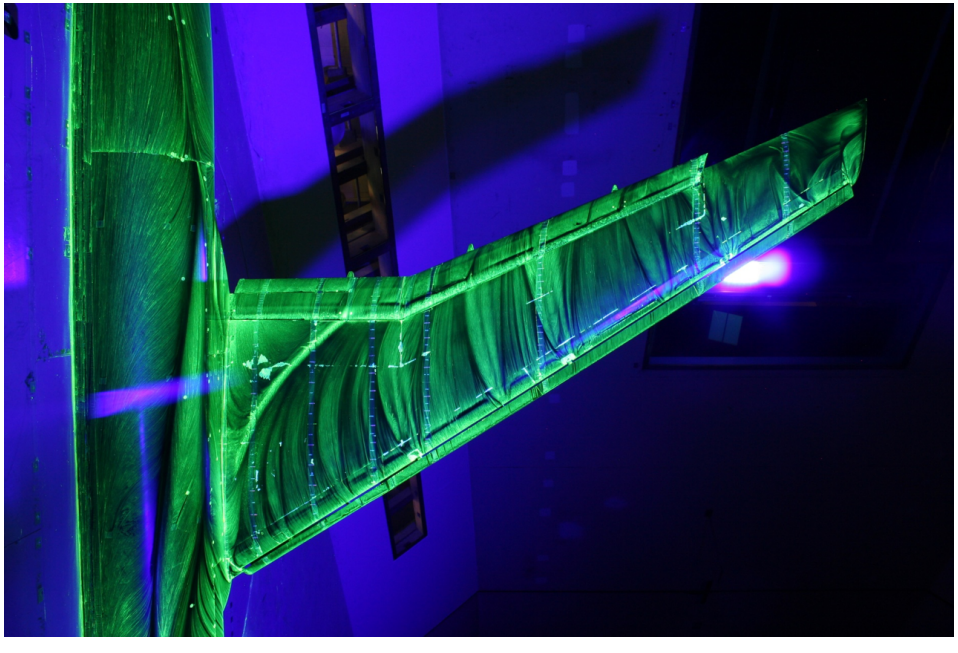


OpenFOAM

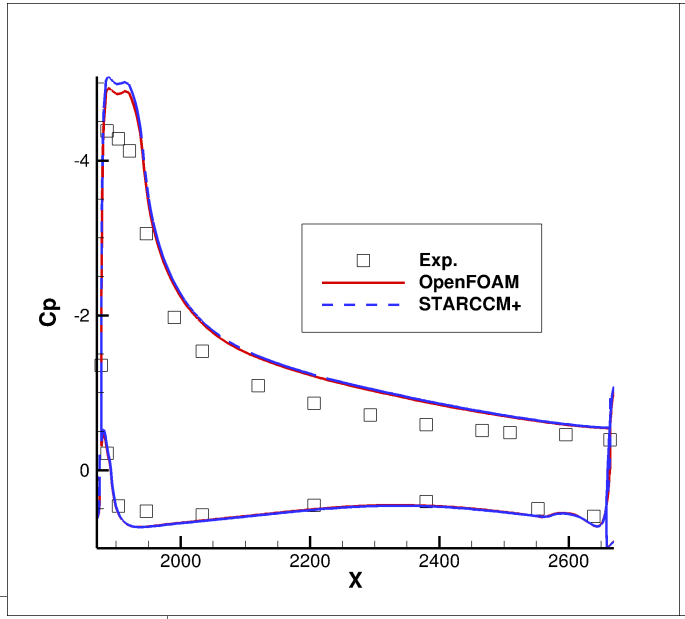


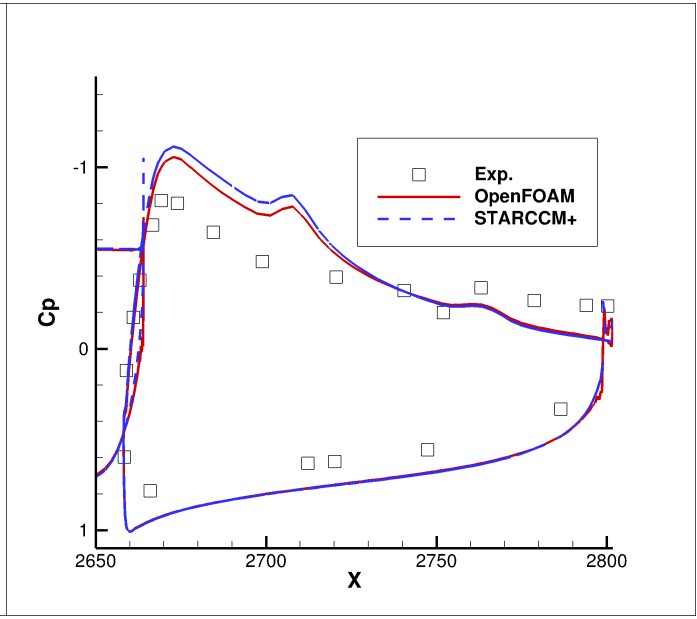
STAR-CCM+

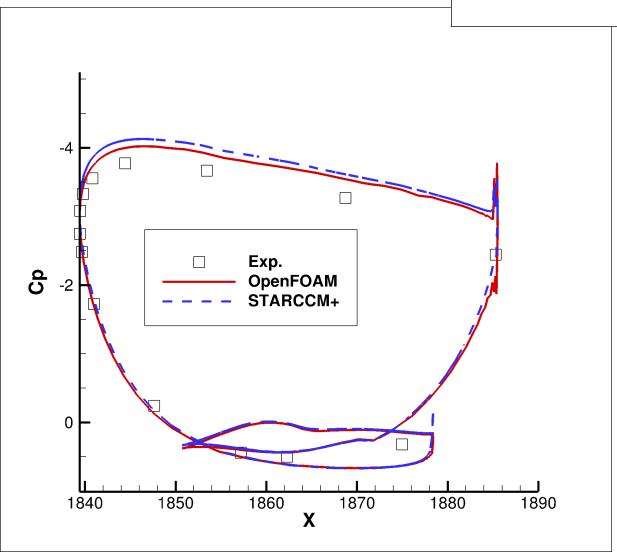
- In-board separation completely under-predicted (SA Turb)
- Over-prediction of outboard losses
- Error cancellation!

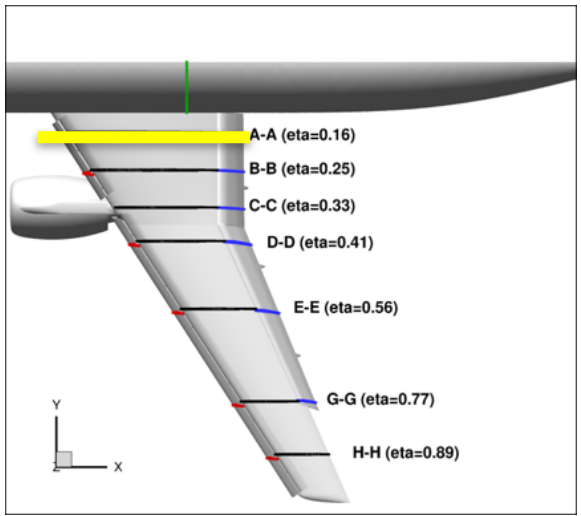


JSM no-nacelle 21.57º – A-A

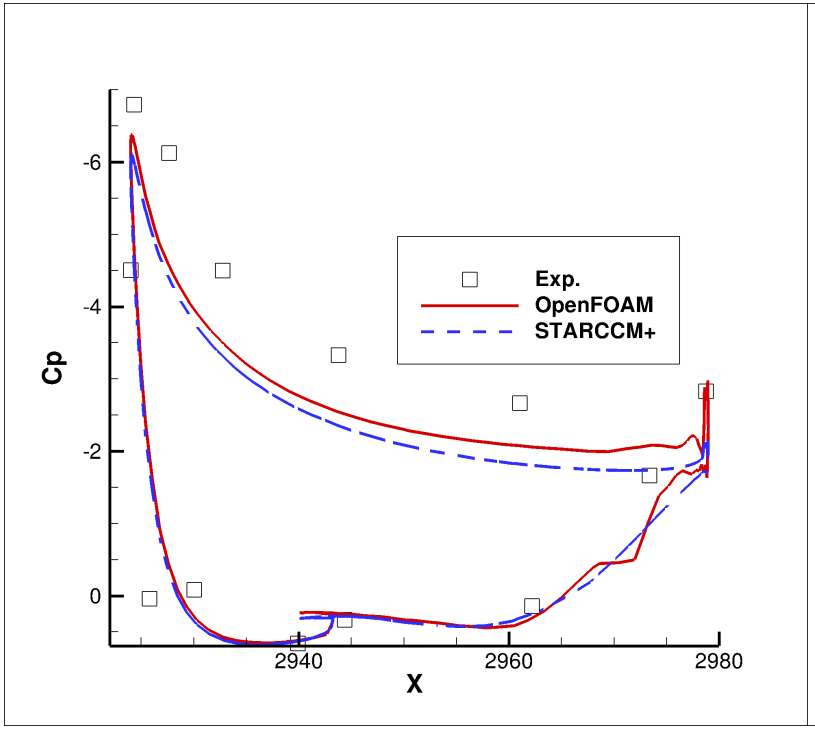


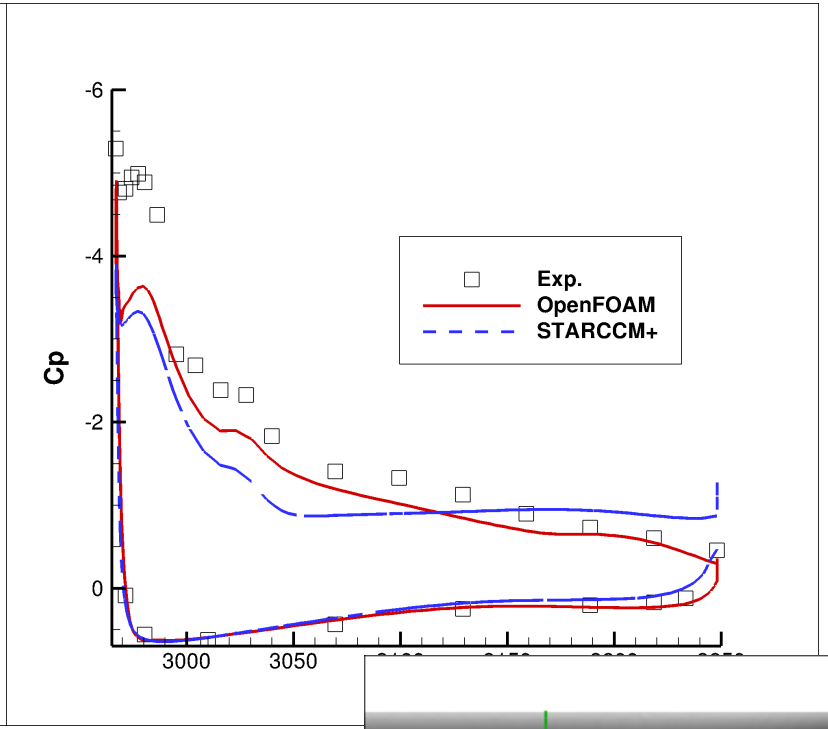


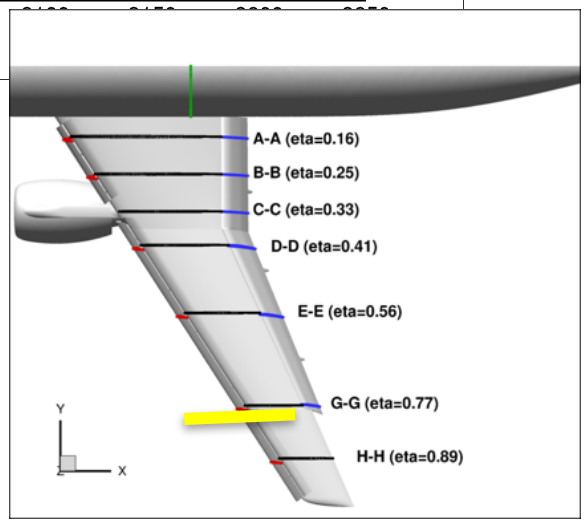




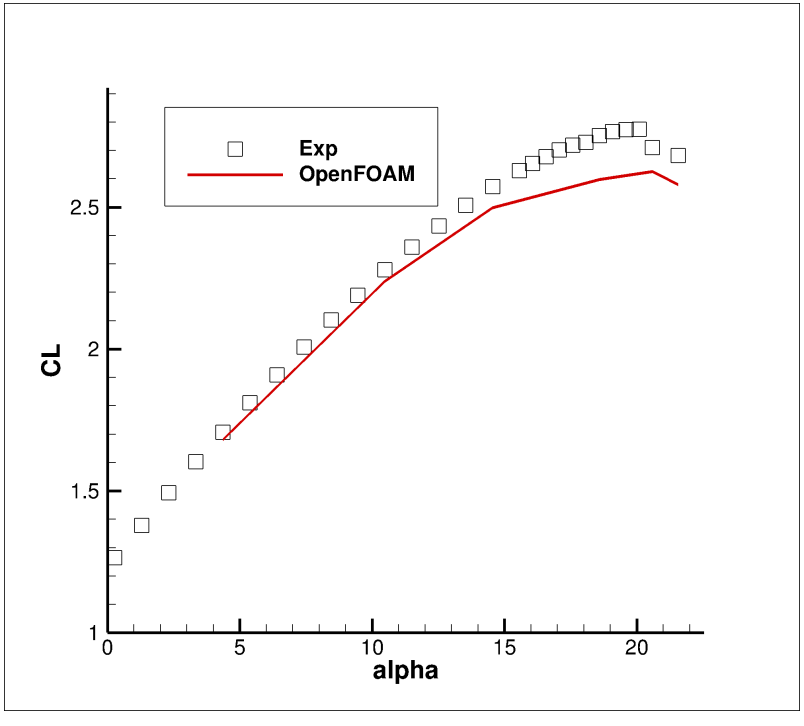
JSM no-nacelle 21.57º – H-H

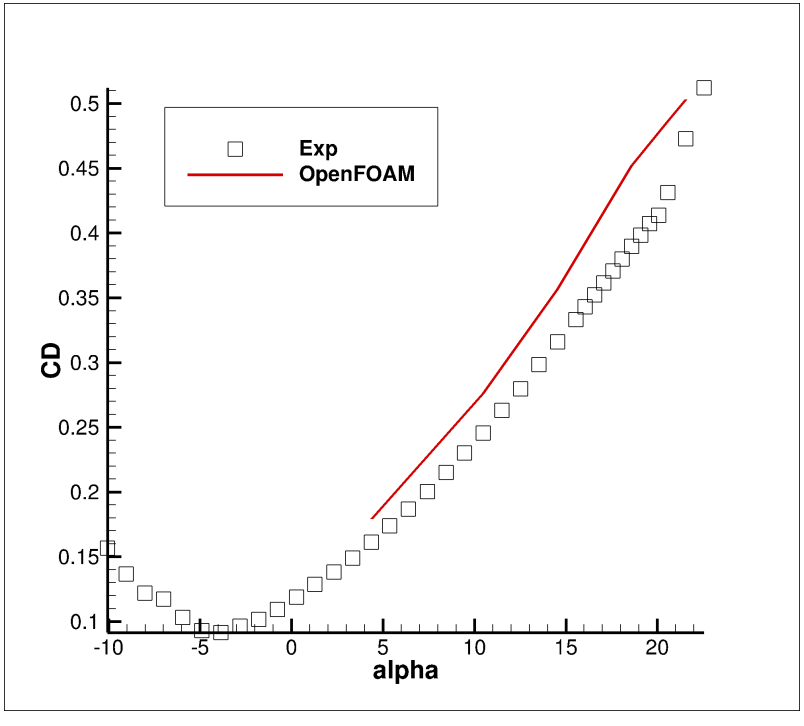






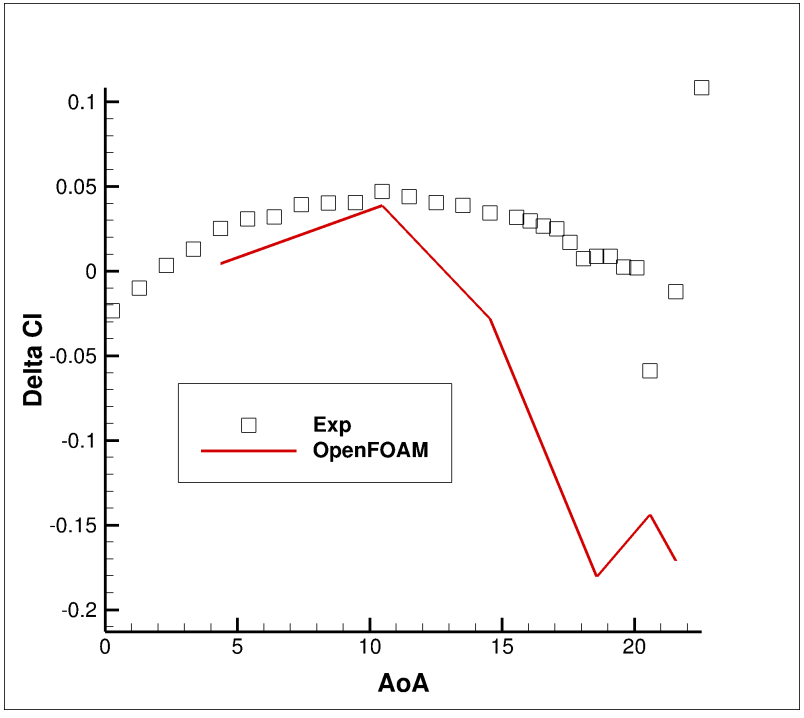
Nacelle-on

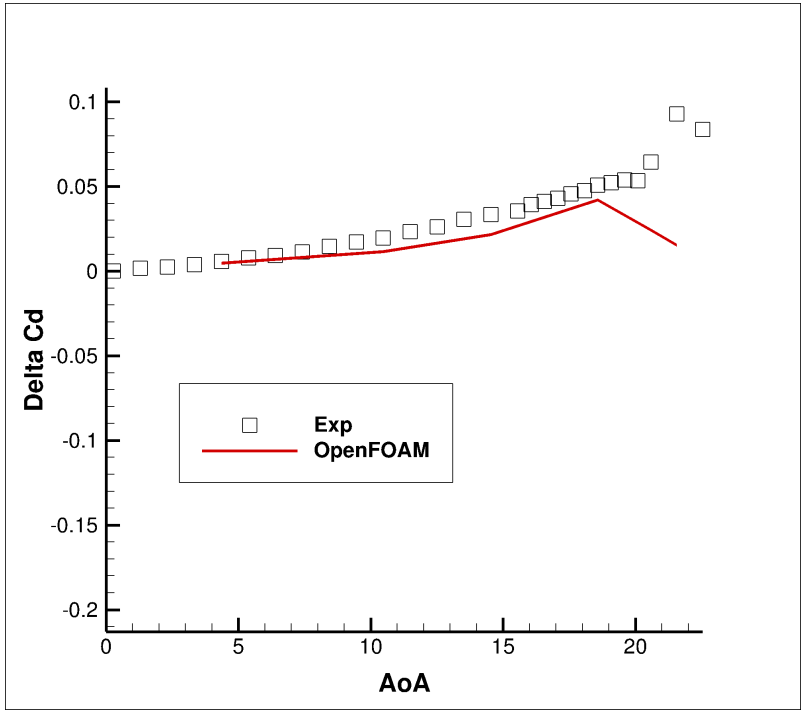




- Early stall compared to experiment
- Similar over-prediction of Drag

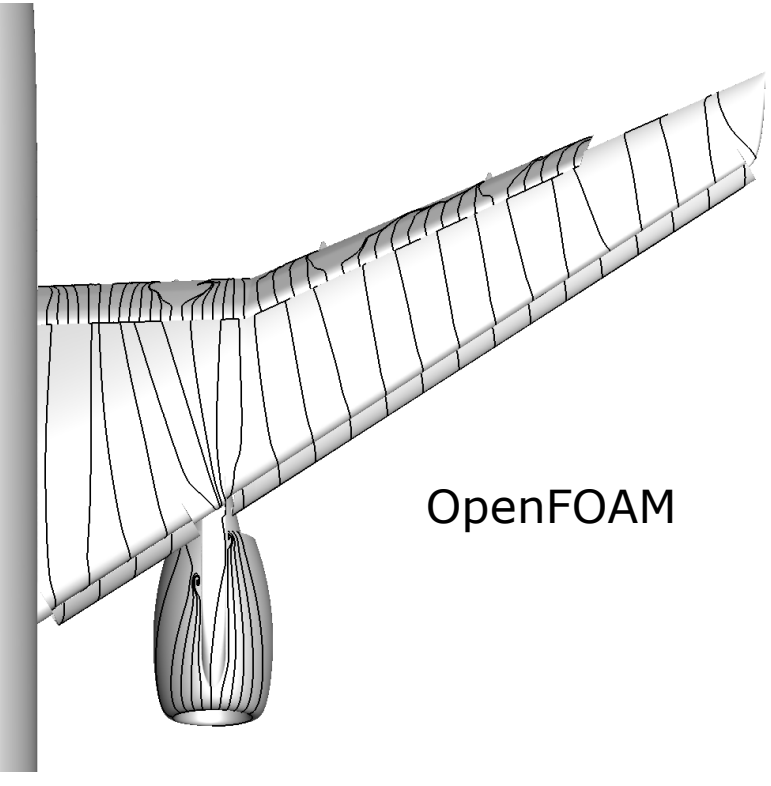
Nacelle on/off delta



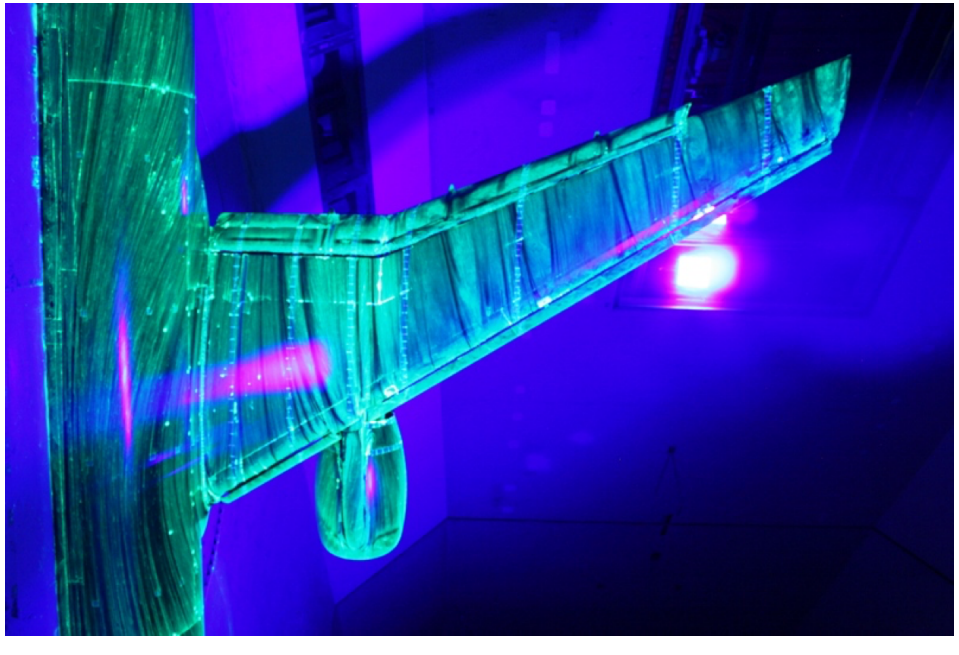


- The in-board separation is missing for nacelle-off from 18.58AoA
- Too large outboard separation

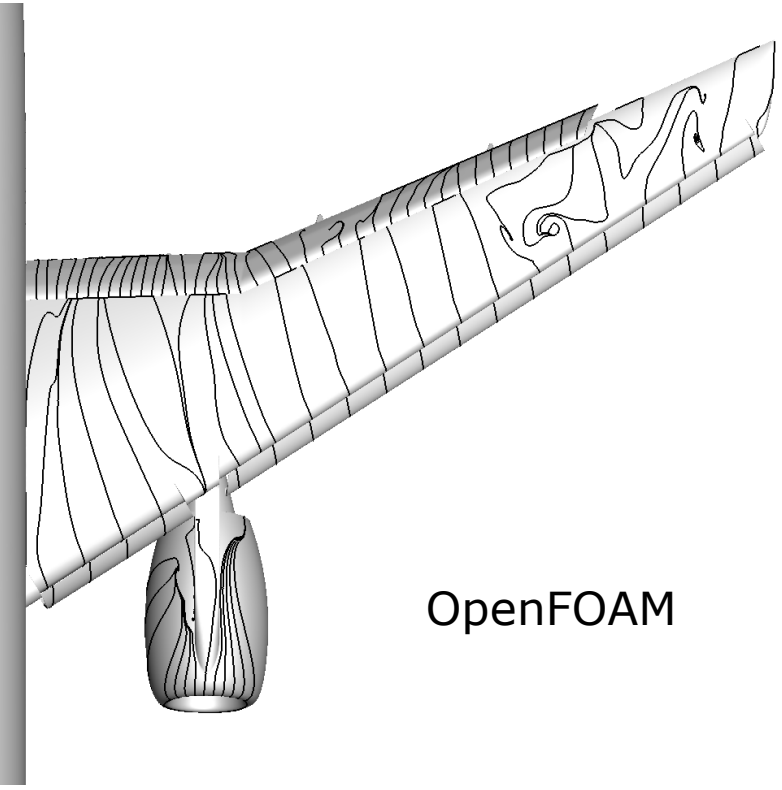
JSM nacelle-on 4.36°



OpenFOAM

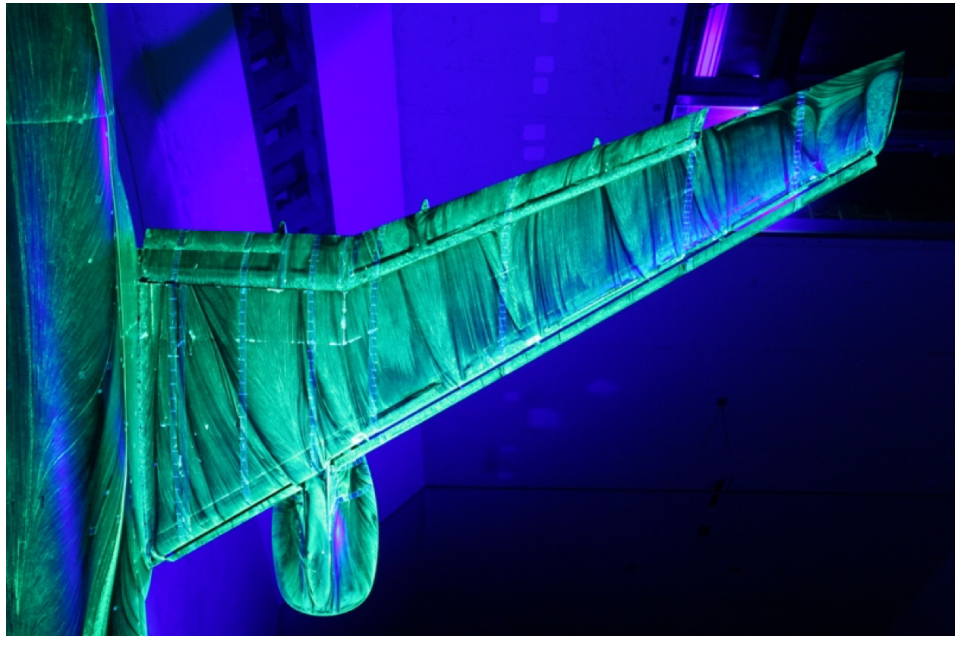


JSM nacelle-on 18.58°

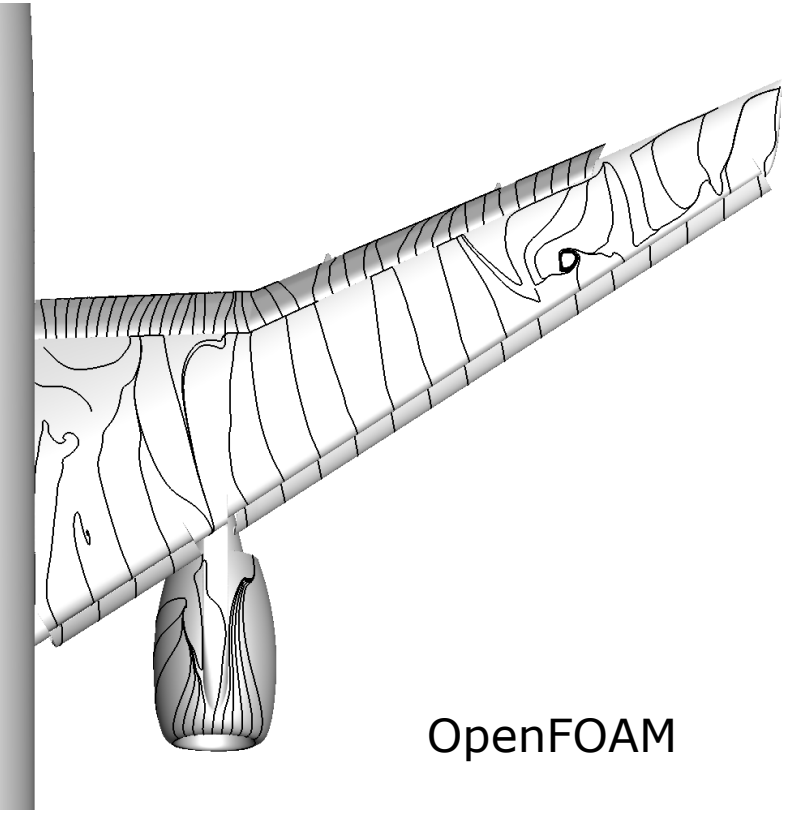


OpenFOAM

- **Over-predicting outboard stall**

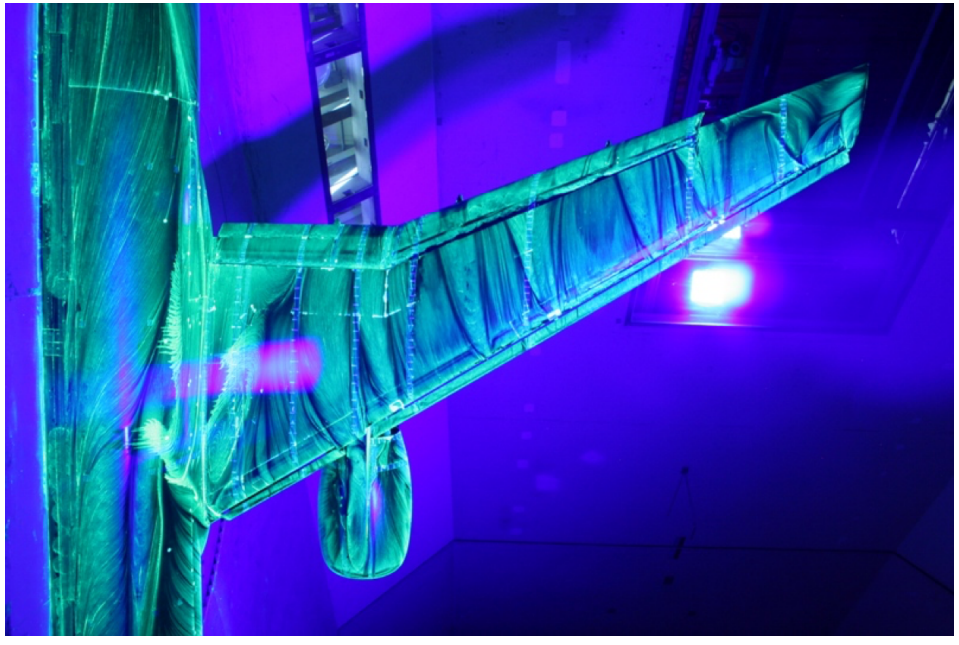


JSM nacelle-on 21.57°



OpenFOAM

- Over-predicting outboard stall
- Capturing in-board separation (unlike no-nacelle case)



Summary (1)

- Honest assessment of a popular open-source code; OpenFOAM
  - Close enough agreement for engineering investigations– average difference is 1% for Lift and Drag between CRM and JSM
  - Requires wall-distance improvement and farfield boundary condition to reduce errors
  - Not as robust as STAR and CFL ~1 meant 100,000 iterations for convergence

Summary (2)

- STAR-CCM+ close to FUN3D/CFL3D for verification case
  - Good agreement with other HLPW partners using SA model
- SA model appears to offer good correlation for lift but for higher AoA missed corner separation for JSM – error cancellation
- Unstructured prism/tet meshing strategy offers good comparison against other grid types


Thank you